AN INVESTIGATION OF THE EFFECTS OF PULSATING CHARGING CURRENT ON THE PERFORMANCE OF LEAD-ACID STORAGE CELLS

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1953

M-29

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PREFACE

The experiment discussed in this report was carried on from September, 1952, to May, 1953, at the U. S. Naval Postgraduate School, Monterey, California. The work was done in partial fulfillment of the requirements for the degree of Master of Science and in a desire to improve submarine storage battery performance. The investigators are grateful for the encouragement of Professor Allen E. Vivell and the technical assistance of Mr. Harold Schauer.

Carvel Hall Blair

Charles Eugene Donaldson, III

Monterey, California

May, 1953

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TABLE OF SYMBOLS AND ABBREVIATIONS

A -	Cross sectional area of gas collecting vessel.
°C -	Degrees Centigrade.
cps -	Cycles per second.
°F -	Degrees Fahrenheit.
F -	Fisher's statistical variable; Faraday's constant.
h -	Height of water in gas collecting vessel.
I -	Current.
KVA -	Kilo-volt amperes.
KW -	Kilowatts.
n -	Number of observations.
Q -	Charge, in ampere-hours.
R -	Gas constant.
r -	Virtual cell resistance.
s	Sample standard deviation.
s^2 -	Sample variance.
T -	Temperature.
t -	Time.
V -	Volume of saturated gas at 27°C., atmospheric pressure.
V' -	Uncorrected volume of gas.
W -	Energy in watt-hours.
X -	Sample mean.
η -	Efficiency.
θ -	Dacos' time fraction.
μ -	Population mean.
σ -	Population standard deviation.
σ^2 -	Population variance.

Subscripts:

c -	Pertaining to total charge.
d -	Pertaining to discharge.
f -	Pertaining to finishing rate charge.
m -	Mean.
s -	Pertaining to starting rate charge.

SUMMARY

Objective: An investigation of the effects of charging lead-acid storage cells with a pulsating direct current.

General Methods: A charging circuit was designed and constructed to permit charging a battery of three 24-ampere-hour cells with a pulsating direct current, carefully regulated and metered at 2.4 amperes average value, at a frequency variable from 0.2 to 400 cycles per second. The battery was repeatedly cycled under similar conditions except for frequency of the finishing rate charging current, which was varied from 0.5 to 400 cycles. Control charges, with a steady, non-pulsating current, were also conducted. The gas generation, ampere-hour efficiency, and watt-hour efficiency were determined for each charge, and an attempt was made to correlate these with frequency.

Findings: The investigators demonstrated qualitatively that charging a battery with pulsating current improved performance. For Willard ER-24-2 cells, the best results were observed at a frequency of about 0.5 to 1.0 cycles per second. Further tests, employing statistical methods, are necessary to find the reason for this improvement and to determine quantitatively its magnitude.

CHAPTER I

PREVIOUS INVESTIGATIONS

An investigation of the effects of a pulsating battery-charging current leads the experimenter into almost virgin territory. The pioneer in the field is F. Dacos of the University of Liége, who summarized his findings in the Revue Universelle des Mines. [3] His experiments compared generator charging of lead-acid cells to rectifier charging. (In a letter to the investigators Dacos stated that he used a 50 cycle per second current and an unfiltered, full-wave dry rectifier.) He concluded that charging with a pulsating current produced "remarkably better" performance than charging with a steady current. In particular, pulsing the current caused:

(1) Higher efficiencies, both watt-hour and ampere-hour;

(2) Decreased gassing (by an average of 18% in 100 tests);

(3) Higher mean voltage on discharge;

(4) Decreased "shedding" of active material; and

(5) Increased cell life (by 34% in a single longevity test).

(6) Decreased consumption of water.

Dacos found the shape of the current pulses to be relatively unimportant. His brief, qualitative explanation of these phenomena will be discussed later in this paper.

The literature revealed no other reference to battery performance as affected by pulsating charging current, even in Vinal's authoritative Storage Batteries [12]. Vinal's discussion of the physical chemistry of the lead-acid cell, however, suggests an attack on an explanation of these results and will be discussed below.

G. W. Jernstedt, of the Westinghouse Electric Corporation, investigated and patented an electroplating process in which the plating current is periodically reversed. In the Westinghouse Engineer [7] he described the circuits and apparatus used, and gave a qualitative theory explaining the improved plating produced by this method. Neither this article, however, nor any of the other references to periodic-reversal, or "PR" plating (see Bibliography) suggested an explanation for the effects of pulsating charging on storage batteries.

Guided by these references and some experience with submarine storage batteries, the investigators decided to conduct an experiment in which a lead-acid battery would be repeatedly cycled, the finishing-rate current being pulsed at different frequencies. Steady current control charges were to be made for comparison. It was hoped to discover whether benefits similar to Dacos' could be obtained if the charging current were pulsed at a frequency on the order of 1 or 2 cycles per second. Varying the field of a conventional submarine main generator, perhaps by a commercial PR electroplating control, could produce such a current, while a higher frequency on the order of 50 cycles would be difficult to obtain. While the improved performance achieved by Dacos would be valuable in any battery, it would be exceptionally desirable in a submarine battery where high performance and minimum gassing are essential. Since the experimental setup could be adapted for higher frequency work, the frequency range was extended from 0.5 to 400 cycles per second.

CHAPTER II

PROCEDURE

The first step in a study of pulsating-current charging, the investigators decided, should be to determine the effects on cell performance rather than to study electro-chemical phenomena. Several motives prompted this decision:

(1) Unless improved performance were found to exist, there would be little incentive to study the electro-chemical reactions involved.

(2) The background of the investigators was electrical rather than chemical.

(3) Available laboratory facilities lent themselves better to measuring and controlling electrical rather than chemical variables.

It was therefore decided to study the variation with pulse repetition frequency of the following indices of cell performance:

(1) Ampere-hours per charge, and ampere-hour efficiency;

(2) Watt-hours per charge, and watt-hour efficiency;

(3) Gas generation per charge, per watt-hour, and per ampere-hour; and

(4) Duration of charge.

The general scheme was to connect several cells in series and repeatedly cycle the battery. Since variations in ambient temperature were small, temperature was left uncontrolled with the thought that its effect could be neglected. Otherwise all cycles were as nearly identical as possible except that the current during the finishing rate of each charge was pulsed at a different frequency. Average current was kept the same for each charge.

Thus any variation in performance among the cycles should have been due only to the variation in frequency.

A program of experimental work was laid out to determine these data. It later turned out to be too ambitious for the time available, and only parts a, b, c, and d were completed. The schedule, with the approximate times of laboratory and shop work required, was:

a. Design, construct, and test the experimental setup (20 weeks).

b. Cycle the battery at frequencies of 0.5, 1, 3, 7.8, 20, 40, 100, and 400 cycles. Use square pulses at low frequencies, half wave rectification at higher frequencies. (4 weeks)

c. Cycle the battery several times with steady current charging for a comparison with step b. (2 weeks)

d. Investigate reproducibility of results of steps b and c. (1 week)

e. If step d reveals low reproducibility, repeat steps b and c often enough to obtain an accurate mean for each frequency. A statistical analysis of the results of steps b and c will be required to determine how many additional runs at each frequency are required.

f. Repeat these steps for different wave shapes including full wave rectification and pulsed field excitation.

The experimental setup was designed along the lines of Figure 1, which shows a simplified block diagram of the equipment. In general, the battery was discharged for a predetermined number of ampere-hours, then fully charged. The charge was considered to be completed when cell voltage ceased to rise. The gas generated in each cell during the finishing rate was collected and measured. Cell current and voltages were recorded. Electrolyte

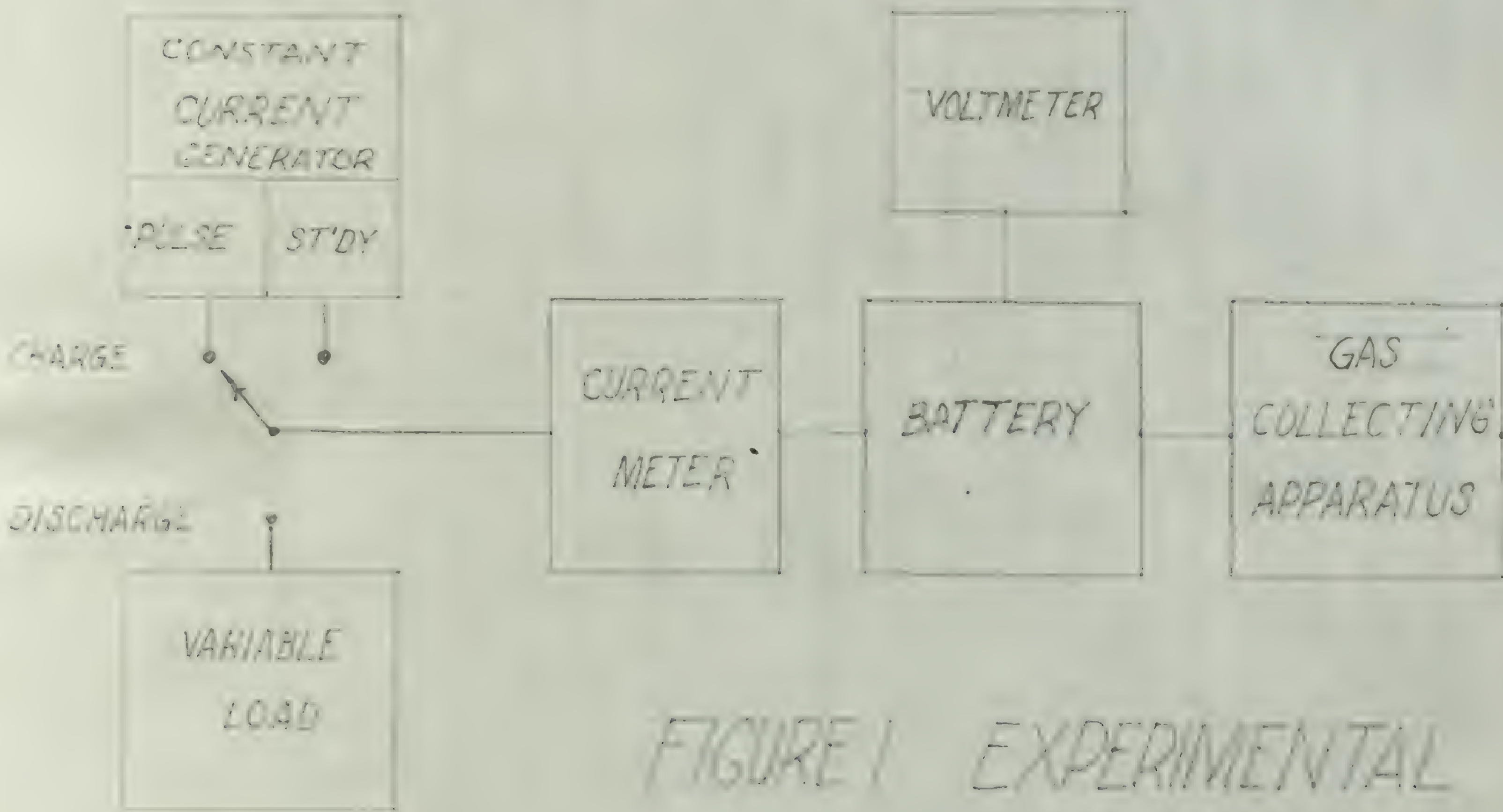
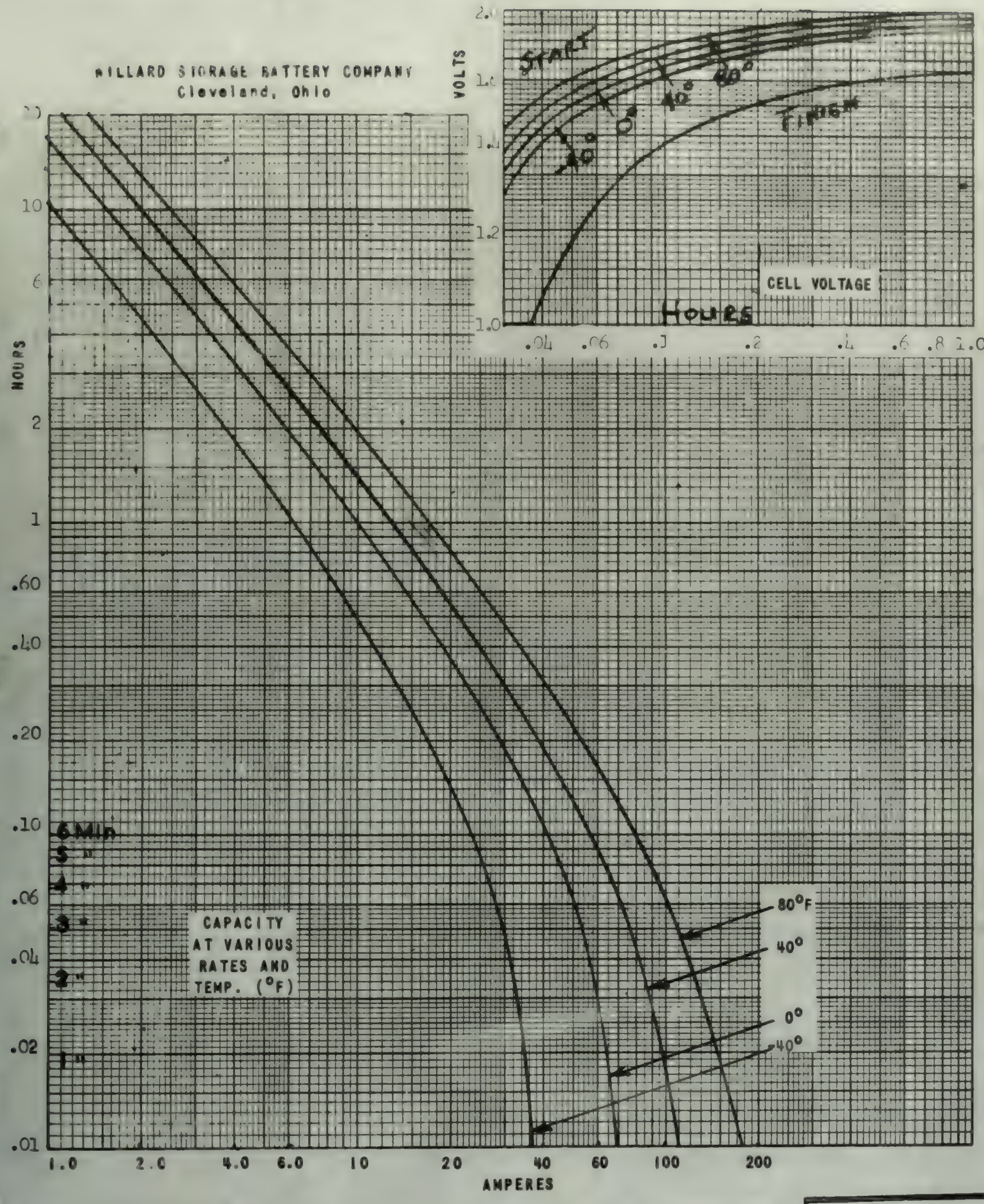


FIGURE 1 EXPERIMENTAL SETUP

temperature was measured but not regulated.

To regulate and measure these simple data (voltage, current, gas volume, and temperature) required a more complicated arrangement than originally anticipated. Like Topsy it "just growed", until sometimes ten pieces of relatively large rotating machinery had to be run simultaneously. The details of the setup are given at length in Appendix A. As the experiment proceeded, some improvements were made, and some were noted but could not be effected. In particular, the substitution of recording instruments for indicating instruments would have simplified both the regulating and data-taking problems. This and other improvements are more fully discussed in Chapter V.

It was decided to use three Willard Type ER-24-2 cells for the experiment. This cell is a small, plastic-encased, non-spill type having a nominal capacity of 24 ampere-hours with a specific gravity of 1.280. The manufacturer's performance curves are shown in Figure 2 and the Bureau of Ships drawing in Figure 3. A small cell with a low charging current was necessary if square current pulses were to be produced by relaying. A small cell also would generate a relatively small volume of gas and minimize the problem of gas collection and metering and the hazard from hydrogen-oxygen explosions. While realizing that this cell is a far cry from the 5000 ampere-hour submarine cell in which they were primarily interested, the investigators considered that both cells would react similarly to pulsating-current charges. The reactions are the same in each cell, and the voltage, specific gravity, and plate-current density



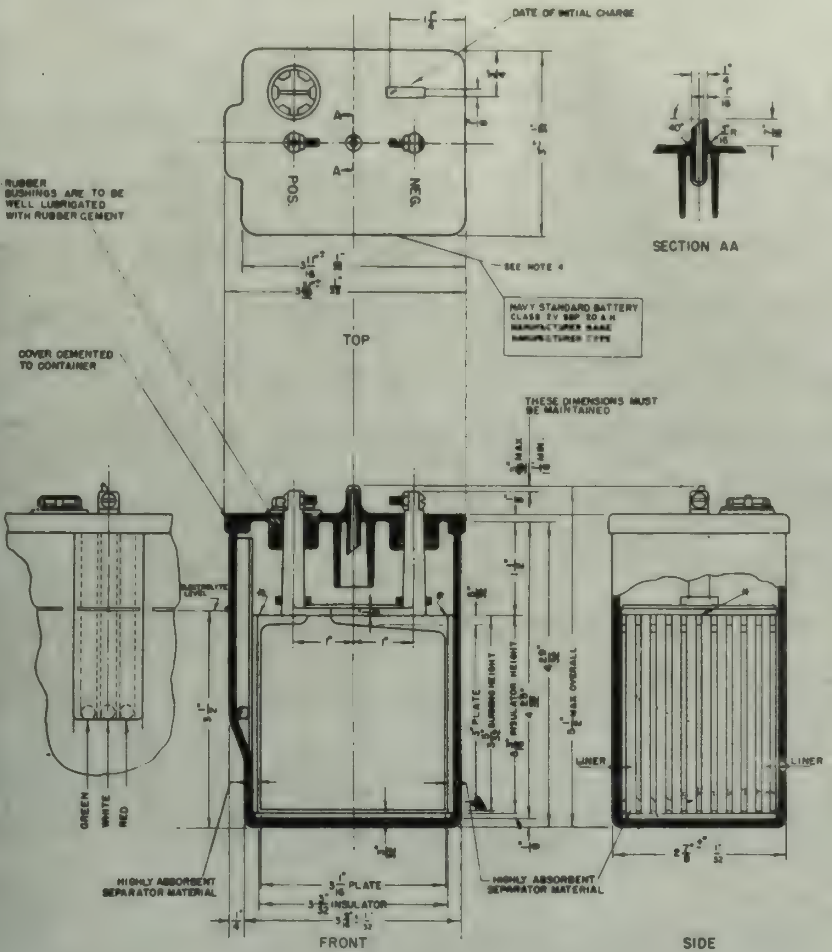
DRY WEIGHT 2.86 POUNDS
WET WEIGHT 3.82 POUNDS

TERMINAL VOLTAGE 2.0 VOLTS

MAXIMUM DIMENSIONS
LENGTH 3 31/32 IN.
WIDTH 3 IN.
HEIGHT 5 1/2 IN.

2 VOLTS
TYPE ER-24-2
DATE 5-29-50
CURVE 17

FIGURE 2 PERFORMANCE CURVES FOR WILLARD CELL TYPE ER-24-2



NOTES

1. BATTERY INDICATOR BALLS
   GREEN RISES WHEN FULLY CHARGED
   WHITE DROPS WHEN 50% DISCHARGED
   RED DROPS WHEN 90% DISCHARGED
2. CEMENT LINER IN PLACE AT POINTS INDICATED BY ✱
3. THE CASE AND COVER SHALL BE MADE OF POLYSTYRENE OR OTHER APPROVED MATERIAL. (NOT HARD RUBBER)
4. LETTERS TO BE STAMPED, MOLDED OR ENGRAVED ON CASE IN AN APPROVED METHOD.

Nº	REMARKS	DATE		
1	NAME PLATE DATA AND NOTE 4 ADDED; TITLE BLOCK CHANGED [illegible] TO 20 AH	[illegible]	[illegible]	T.R.C.

ALTERATIONS

PORTABLE STORAGE BATTERY

CLASS 2V-SBP-20AH

SCALE 12 INCHES = 1 FOOT

BUREAU OF SHIPS
NAVY DEPARTMENT

WASHINGTON, D.C. [illegible]

FOR CHIEF OF BUREAU

DRAWN BY / TRACED BY / INSPECTED BY / CHIEF DRFTS / HEAD OF DIV.	INDEX	GROUP	FILE Nº
[illegible signatures]	9	S	5408L ALT. 1

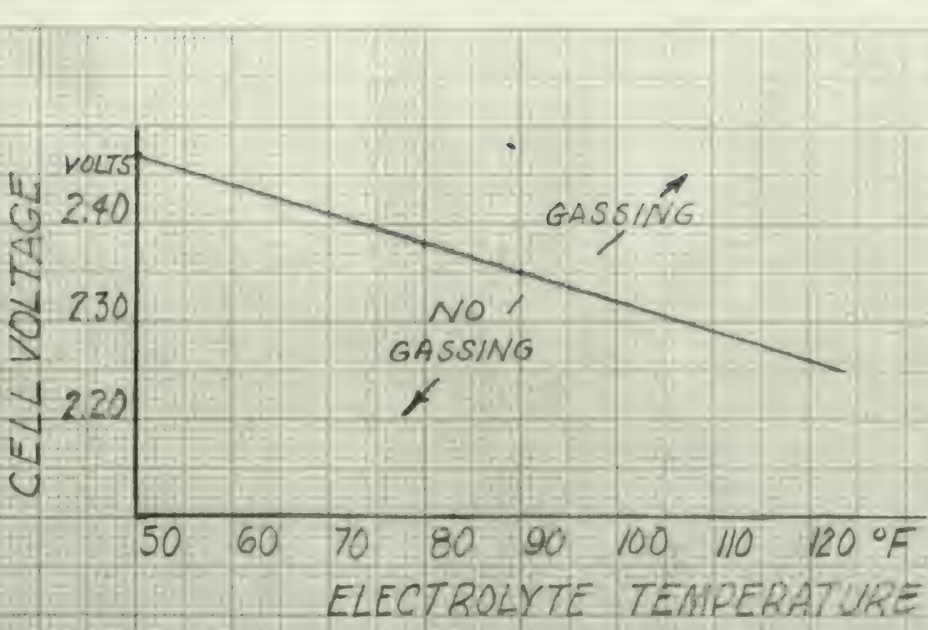
FIGURE 3

TEST CELL

are similar. Furthermore there was no available equipment for cycling a cell of very large capacity.

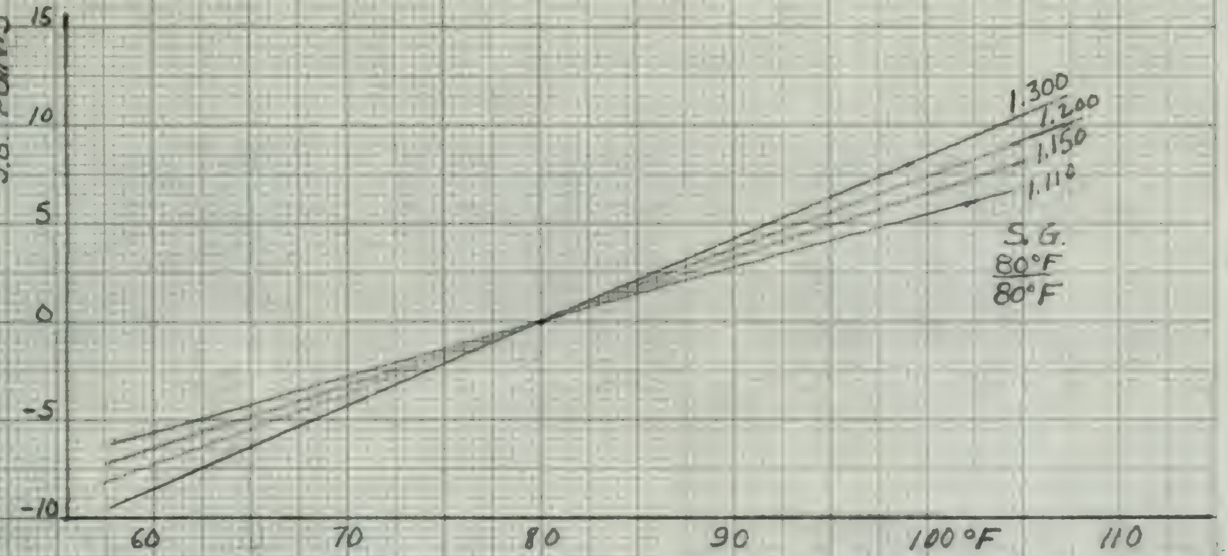
The cells were obtained in the charged and dry condition, with the cell openings sealed. All cells were filled with 365 milliliters of reagent grade sulfuric acid of 1.280 specific gravity. After charging for 24 hours, as recommended by the manufacturer, the cells were cycled 4 times. Discharges were at 15 amperes for 48 minutes, or 12 ampere-hours. Charges used two steps of constant current with a starting rate of 6 amperes and a finishing rate of 2.4 amperes. Current was lowered to the finishing rate when any cell reached the gassing voltage determined from the Temperature-Voltage-Gassing curve shown in Figure 4. By the fourth preliminary cycle, cell voltages at end of discharge and at end of charge were substantially constant, and it was considered that no appreciable change of cell characteristics would occur with further cycling.

To be able to fill a hydrometer barrel, it was necessary to keep the electrolyte level about one centimeter above the level line on the cell jar. The gravity of this upper layer of electrolyte changed very slowly, dropping only ten or twenty points during a one-hour discharge. Since gravity readings were not significant, the filling plugs were inserted and sealed with wax after the fourth preliminary cycle. No more gravities were taken until the completion of the experiment, when they were again read, and found to have dropped about 10 points. This small change was assumed to have negligible effect. Hydrometer readings were corrected



TEMPERATURE-VOLTAGE-GASSING CURVE

FIGURE 4



CORRECTION FOR 80°F/80°F SPECIFIC GRAVITY

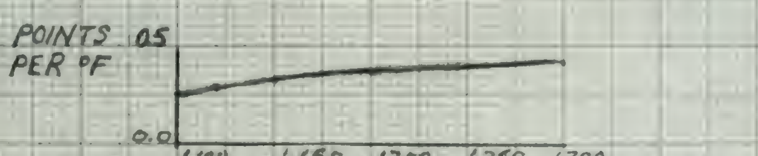
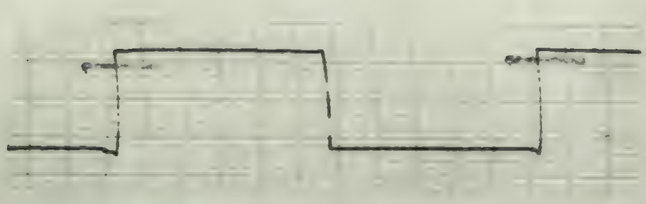
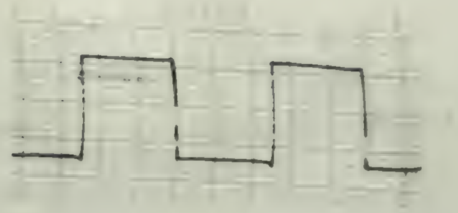


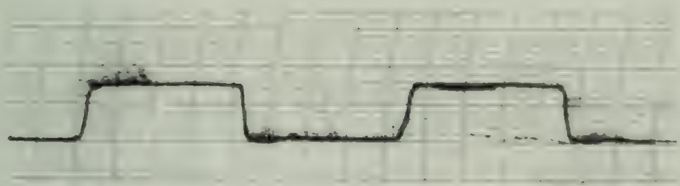
FIGURE 5 TEMPERATURE CORRECTIONS TO HYDROMETER



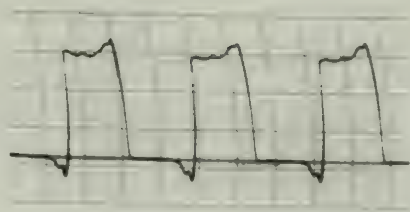
0.5 cps



1 cps



3 cps

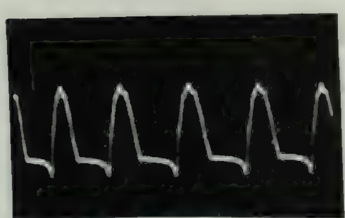


7.8 cps

20 cps

40 cps

100 cps



400 cps

steady(with
zero current datum)

FIGURE 6. CHARGING CURRENT PULSE SHAPES

Notes
1. Scales differ among the traces.
2. In each case mean current is 2.4 amperes.
3. Traces below 10 cycles per second by Brush recorder; above 10 cycles by cathode ray oscillograph.

to 80°F/80°F by the curves of Figure 5.

The current pulse shape was chosen as a square wave of equal on and off periods for frequencies below 10 cycles per second. For higher frequencies a half sine wave was used. In both cases the mean value was 2.4 amperes. Figure 6 shows the current wave shapes actually used. In some cases, on and off times were not precisely equal; in others, slot harmonics were prominent. In every case the average value was measured to be 2.4 amperes. Although the same pulse shape, either half-sine or square, would have been desirable for the entire frequency range, practical difficulties prevented it. It proved impractical to operate a relay or switch faster than about 8 cycles per second. When available alternators were run at speeds lower than that corresponding to about 15 cycles per second, it was impossible to generate sufficient voltage. Daese [3, page 17] stated that

> careful trials, made with different forms of rectified alternating current, showed a very light supplementary benefit in gas evolution when one used 3rd harmonic current.

It was consequently assumed that the square wave and the half sine wave would produce similar results. The "steady" current actually had a small slot ripple, but it was believed that the ripple produced no appreciable difference from a truly constant direct current.

After the fourth preliminary cycle the test cycles were begun. Steady and pulsed runs were conducted in a random order to counteract any effect of progressive changes in the battery with cycling. The test cycles followed the same procedure as the preliminary cycles. The cells were discharged for 48 minutes at 15 amperes, then put on charge at 6

amperes steady current. When the gassing voltage was reached on any cell, the current was dropped to 2.4 amperes and gas collection was begun. The finishing rate current was pulsed or steady depending on whether the run was a test run or a control run. The gas was collected, individually for each cell, over water, and kept at atmospheric pressure by a leveling bulb. No attempt was made, nor was it practicable, to separate the hydrogen and oxygen formed at the negative and positive plates respectively. The gas collected was therefore a saturated mixture of hydrogen and oxygen plus the air initially in the collection apparatus. Difficulty with gas leakage was overcome by sealing the filling caps with wax.

During discharges, voltage readings were recorded at 6 minute intervals. During charge, voltage readings were taken at 12 minute intervals until the charge was almost completed. The temperature correction to voltage, 1.1×10^{-4} volts per degree F., was neglected. For the last hour or so, readings of voltage and gas level were taken at 6 minute intervals. Gas volume was corrected for temperature but not for pressure. As explained in Appendix A, the current pulsations were stopped during voltage readings at the lower frequencies and the current maintained at 2.4 amperes steady until the cell voltages were read. Although this procedure masked somewhat the change in performance due to pulsing, it was accepted as a necessary evil. Since cessation of voltage rise was the criterion for determining the end of the charge, it was essential to measure voltage accurately. A ballistic galvanometer could have been used to read the average of the pulsating voltage, but it would have added complications, especially in

maintaining accurate calibration. In any event, the data could be corrected for the amount of time when the current was steady instead of pulsating. An ordinary d'Arsonval movement voltmeter was therefore used for all charges.

Part b of the program was considered completed after runs at 0.5, 1, 3, 7.8, 20, 40, 100, and 400 cycles per second, and part c after 4 steady current control runs. As discussed in Chapter III, it was difficult to reproduce results in the control runs. To discover whether the lack of reproducibility was caused by faulty experimental techniques or was inherent in cell performance, the investigators commenced part d of the program. Five cycles were run under nearly identical conditions, except that electrolyte temperature was allowed to vary over a small range. Each cycle consisted of a discharge at 15 amperes for 10 minutes plus a charge at 2.4 amperes steady current until voltage ceased to rise. Gas was collected as before. Although even a cursory study of the results showed the desirability of more runs, lack of time forced a stop to experimental work. The analysis of results and writing of the report were then undertaken.

CHAPTER III

FINDINGS

The experiment proved several points conclusively and gave somewhat less conclusive answers to several other questions. An incidental conclusion was that the manufacturer overestimated the cell discharge capacity at the 15 ampere rate. According to the curves of Figure 2, the cells should deliver 15 amperes for 71 minutes at 80°F., for 65 minutes at 70°F., or for 60 minutes at 60°F., before cell voltage reached the minimum allowable of 1.65 volts. On one occasion, the cells reached a voltage of 1.62 by the end of a 48 minute discharge at 15 amperes. On another occasion, when the cells were discharged to the low voltage level, they delivered only 80% of rated capacity. The usual voltage at the end of 48 minutes was 1.8, dropping rapidly. Although the discharges were always terminated after 48 minutes, it was exceedingly doubtful whether the cells would have discharged for 17 more minutes without reaching 1.65 volts. A similar conclusion was reached by the Mare Island Naval Shipyard Industrial Laboratory [8] in tests of 12 similar cells. (They were of the same Navy stock number, but manufacturer not specified.) The laboratory found an average ampere-hour efficiency of 94% at the 15 ampere rate, although performance at the 5 minute and 10 hour rates was excellent.

A second conclusion was that fluctuation in cell voltage, when the battery was charged with a pulsating current, decreased as the frequency increased. Voltage ripple, defined as the ratio between voltage fluctuation and mean voltage, decreased from .124 at 0.2 cycles per second

becoming roughly asymptotic to .025 at frequencies above 2 cycles per second. The actual values are shown in Figures 7 and 8.

Frequency	Ripple	Current Shape	Source of Data
0.2	0.124	square	Brush recorder
0.5	0.090	do.	do.
1.0	0.053	do.	do.
3.0	0.025	do.	do.
7.8	0.024	do.	Oscilloscope with voltage calib.
20	0.013	half sine	Oscillograph photo
40	0.017	do.	do.
100	0.027	do.	Oscilloscope with voltage calib.
400	0.024	do.	do.
"Steady"	0.002	ripple	do.

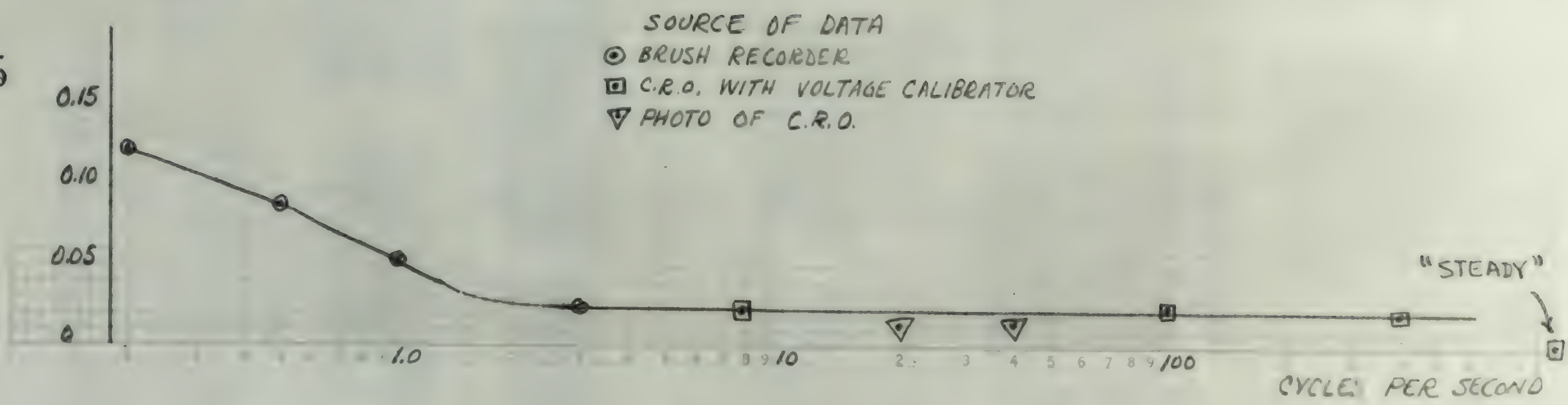
Figure 8. Voltage Ripple

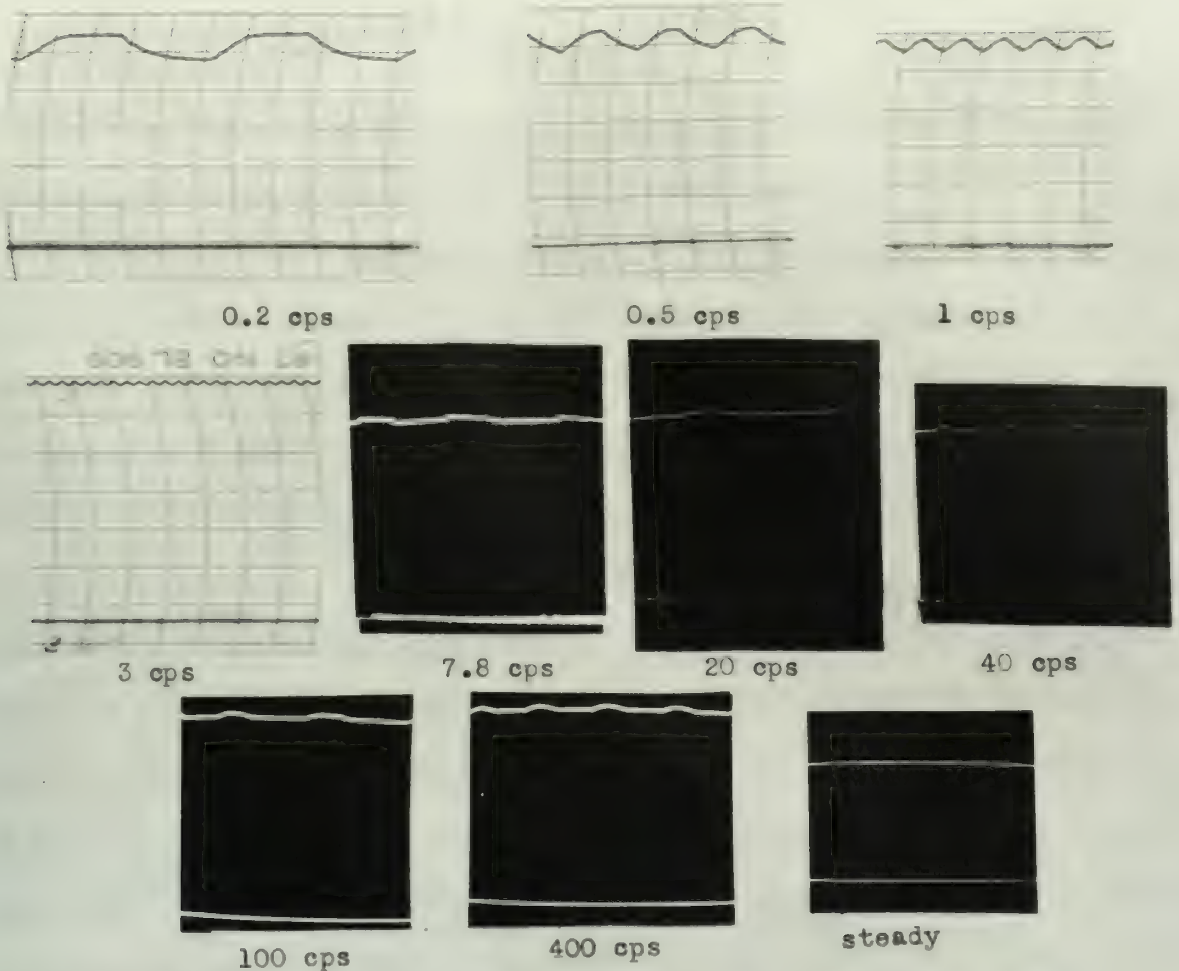
Shapes of the cell voltages and voltage fluctuations are shown in Figure 9, while current shapes are shown in Figure 6 above. Ripple was substantially the same for both current shapes at frequencies above 3 cycles, although the shape of the fluctuation was different. The small, 540 cycle current ripple produced an almost negligible voltage ripple.

A third conclusion is that storage cell performance is not reproducible under ordinary laboratory conditions. Tests run under very similar, if not identical, conditions produced varying results. The investigators were unable to correlate indices of performance with any variable. They were forced to conclude that the indices obtained in this experiment were distributed according to an unknown frequency distribution. The experimentally observed means of these indices cannot be said to equal the true indices. It is possible, however, under certain not unreasonable assumptions, to state a range within which, at a high confidence level, each true index should lie. These confidence limits are shown on the curves

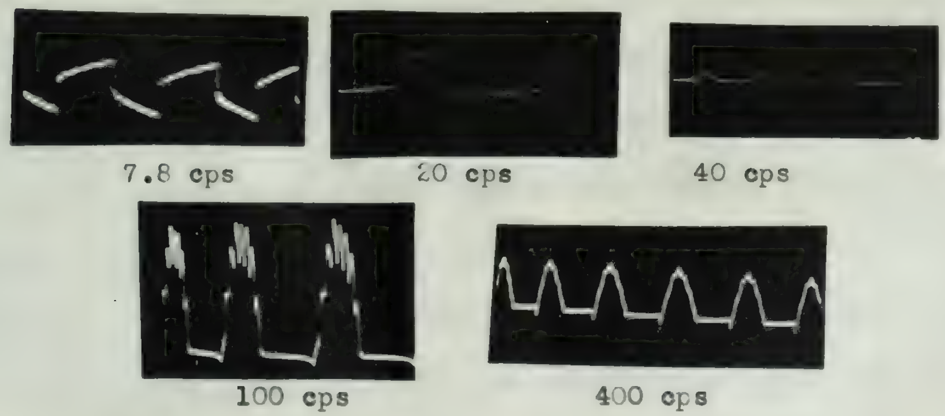
FIGURE 7

VOLTAGE RIPPLE vs. FREQUENCY





A. BATTERY VOLTAGE. Horizontal line at bottom of trace is voltage datum. Voltage 7.5 volts.



B. BATTERY VOLTAGE FLUCTUATION. Scales differ among the traces.

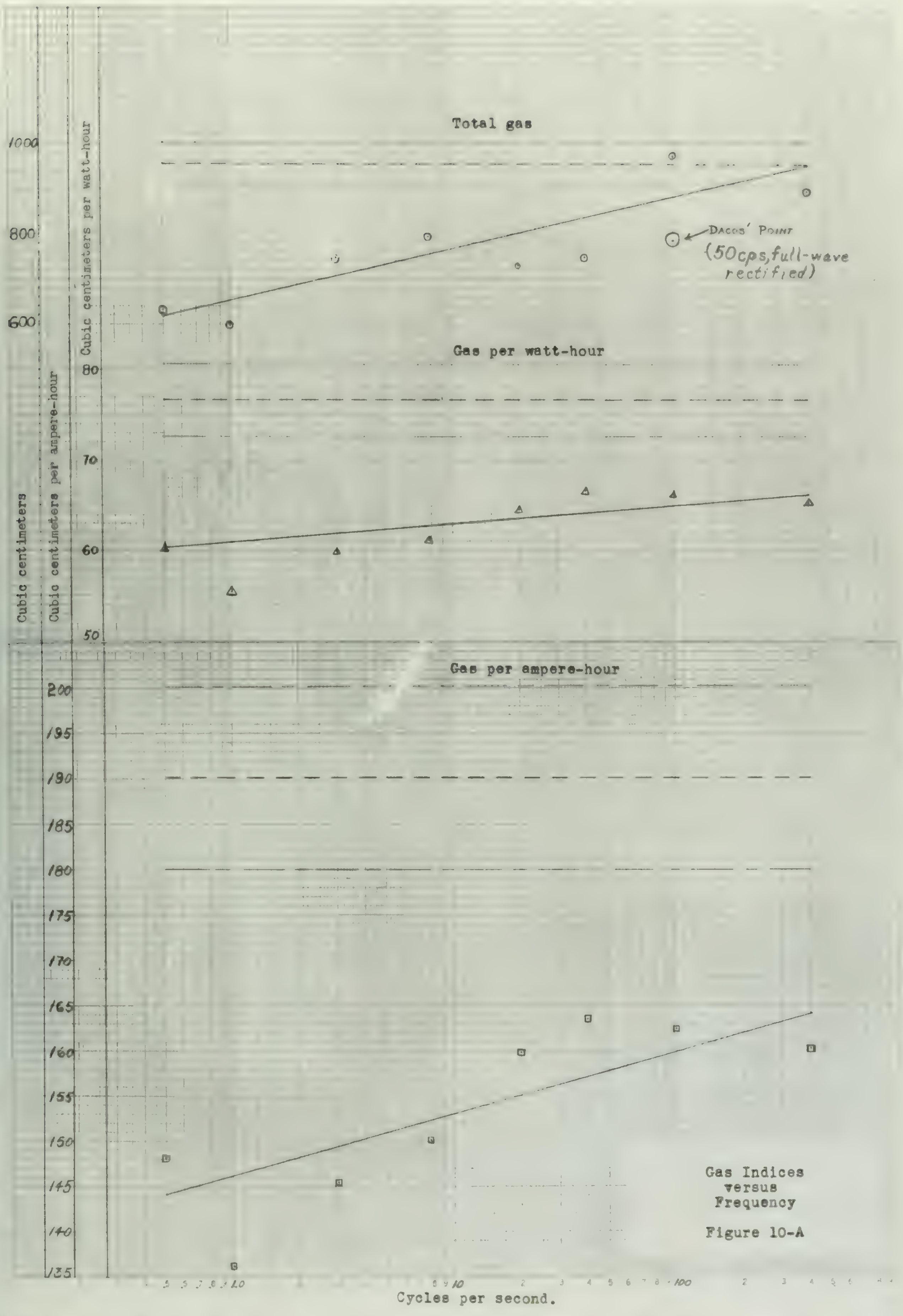
FIGURE 9. VOLTAGE WAVE SHAPES

of Figure 10. Since the statistical analysis is rather lengthy, it is discussed in detail in the following chapter rather than here.

A surprising fact was noted when the volume of gas per ampere-hour during the surcharges was compared with that predicted by Faraday's Law. During the surcharge (portion of charge after voltage ceases to rise) all the charge sent through the cell is transmitted by electrolysis of the water of the electrolyte. Since all the $PbSO_4$ has been transformed into Pb and PbO_2, there is no other mechanism for current flow. One then expects to generate one equivalent of gas at each electrode for every faraday of electricity sent through the cell. If the hydrogen and oxygen were collected together, one would expect to collect about 715 cubic centimeters of the saturated mixture at 27°C. for every ampere-hour of charge. For all frequencies, however, the volume of gas collected was about 444 cubic centimeters per ampere-hour, 62% of the expected value. (Electrochemists would say that the current efficiency was 62%.) Figure 11 shows the values of gas per ampere-hour. The only explanation is that some of the hydrogen and oxygen have recombined into water before escaping from the electrolyte. The investigators then concluded that some of the gas produced prior to the surcharge must also recombine rather than escape. The volume of gas collected was then a function of two phenomena:

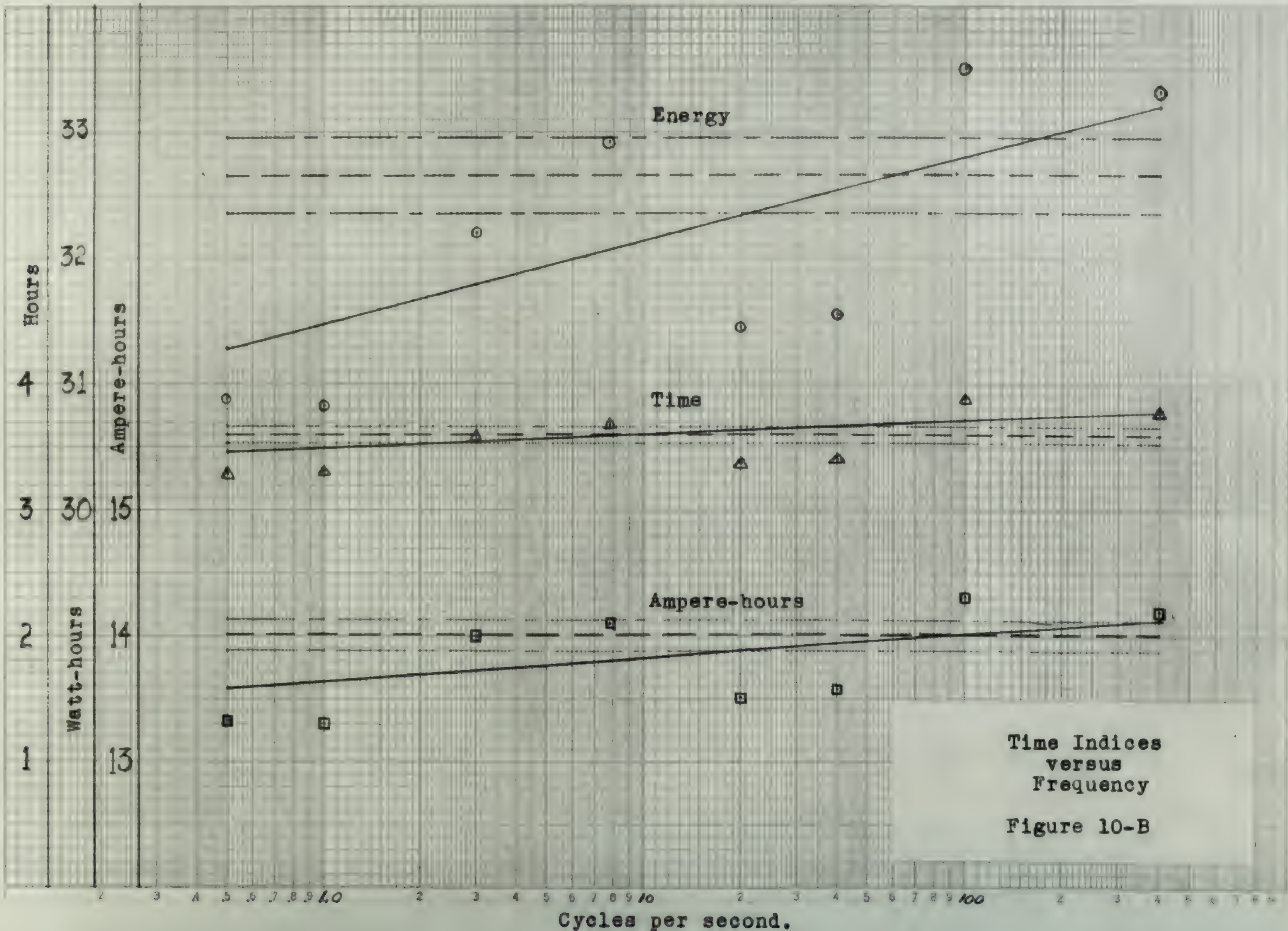
(1) during the gassing before completion of the charge, part of the current desulfated the plates and the rest electrolyzed the water of the electrolyte,

(2) part of the electrolytically produced hydrogen and oxygen recom-



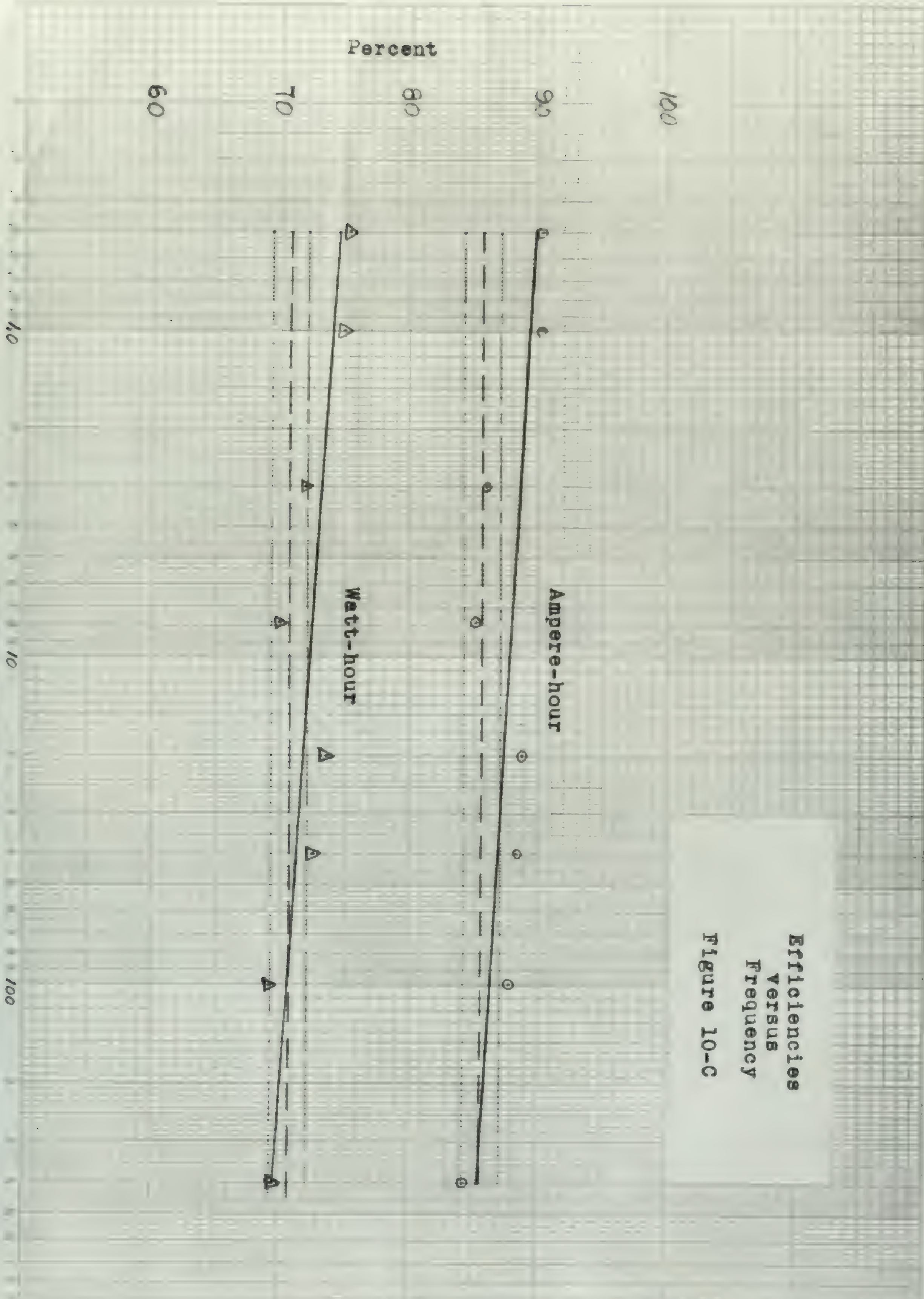
Gas Indices versus Frequency

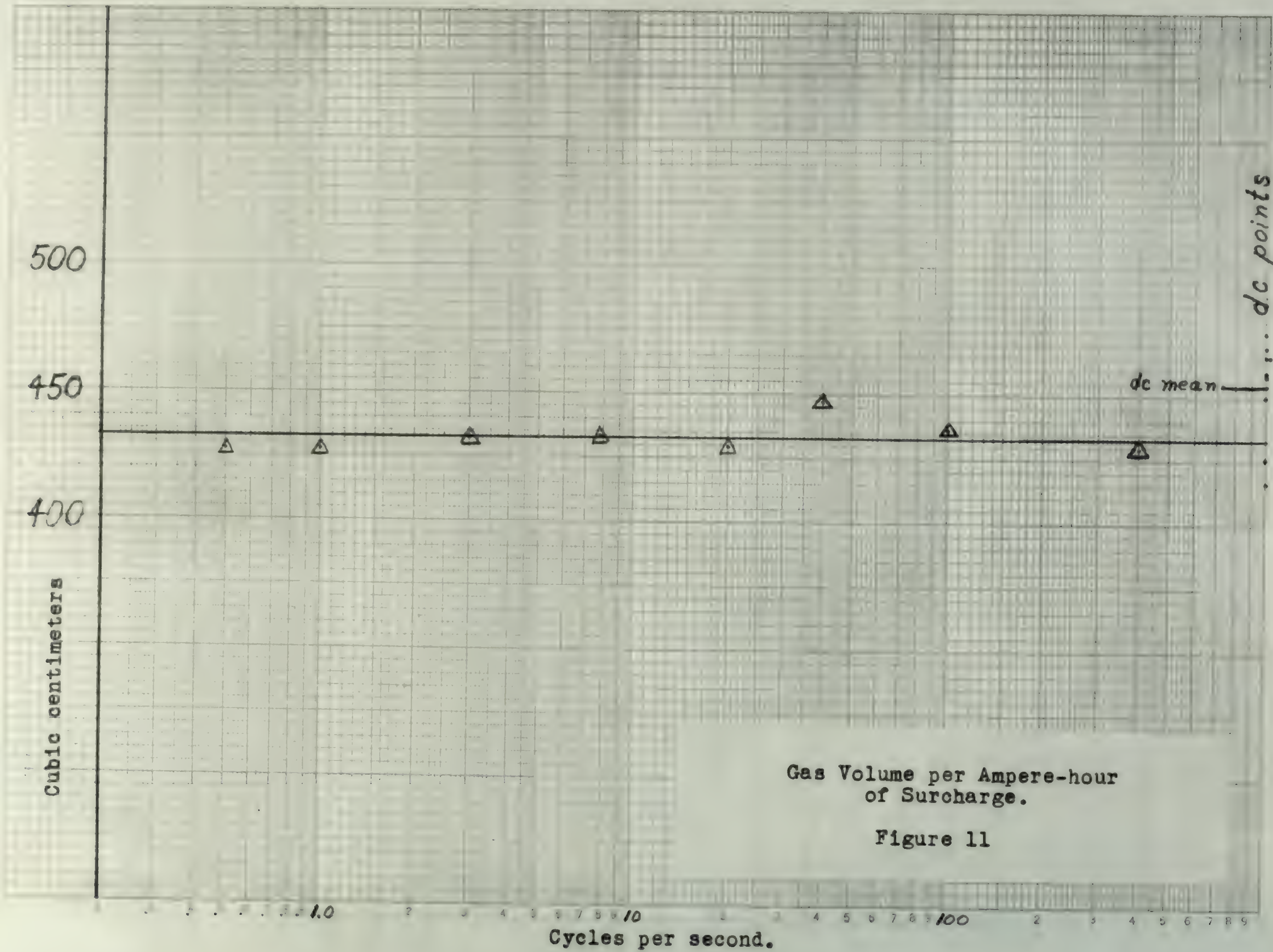
Figure 10-A



Time Indices
versus
Frequency

Figure 10-B


Percent
60
70
80
90
100
1.0
10
100
Cycles per second.
Ampere-hour
Watt-hour
Efficiencies
versus
Frequency
Figure 10-C



Gas Volume per Ampere-hour of Surcharge.

Figure 11

bined into water and part escaped. The relative effect of these two phenomena was not determined, but it was concluded that both occurred to some extent.

The lack of reproducibility of indices of performance prevented giving an exact quantitative answer to the question, "How does battery performance vary with frequency of current pulsation?" It was obvious, however, that pulsating charges improved most indices of performance, particularly at low frequencies on the order of one cycle per second. Figure 10 shows graphically the values of the most important indices. The dashed lines in each graph represent the respective means of the steady current control runs, while the dot-dash lines on either side represent the 90% confidence limits for this mean. That is, the probability is 0.9 that the true value of the index lies between the dot-dash lines. A straight line was fitted to the points for pulsating current as the best estimate of the true situation. Confidence limits in the form of a shaded area centered on this line could have been plotted, but the computation is so tedious and the added information so little that this work was not undertaken. In general, the width of this band would be several times that of the control run confidence band. Quantitative statements being out of order, the following qualitative conclusions were reached for the various indices of performance:

Time: Possibly a slight improvement at the lower frequencies.

Ampere-hours: Possibly a slight improvement at the lower frequencies.

Watt-hours: Slight improvement at the lower frequencies.

Gas evolved: Definite improvement at the lower frequencies; little or none above 100 cycles per second.

Gas per ampere-hour and per watt-hour: Decided improvement at all frequencies tested, greatest at the lower frequencies.

Efficiencies: Slight improvement at the lower frequencies.

In summary, the greatest benefits were noted in gas evolution, with slight improvement in other indices.

[illegible]: Notable improvement at all frequencies tested, greatest at the lower frequencies.

[illegible]: Slight improvement at the lower frequencies.

In summary, the greatest benefits were noted in gas absorption, with slight improvement in other indices.

CHAPTER IV

DISCUSSION OF RESULTS

According to the double sulfate theory, the reaction in a lead acid cell is:

$$2\ PbSO_4 + 2H_2O \rightleftarrows PbO_2 + Pb + 2H_2SO_4.$$

During charge the reaction goes from left to right. According to Vinal [12, page 171] the cell terminal voltage is:

$$V = Ir + 1.87 + \frac{RT}{2F} \ln \left\{ \frac{[Pb^{++++}]}{[Pb^{++}]^2} \right\},$$

where

I = current

r = cell internal resistance (virtual)

R = universal gas constant

T = absolute temperature, ^{o}Rankine.

F = Faraday's constant

$[Pb^{++++}]$ = concentration of tetravalent lead ions

$[Pb^{++}]$ = concentration of bivalent lead ions.

It can be shown that the concentration of the tetravalent ion increases and that of the bivalent ion decreases as the charge proceeds, the voltage thus increasing. Cell temperature tends to rise because of I^2r heating as well as because of the heat of this exothermic reaction, and cell voltage is further increased.

Electrolysis of water occurs at a voltage which varies linearly with temperature. As shown in Figure 4 above, the value is 2.38 volts at 80°F

and decreases as temperature increases. This voltage is usually reached when about 90% of the ampere-hours discharged have been replaced. By this time the desulfating reaction, which proceeds into the plates layer by layer, has reached almost the mid-plane of the plates. When electrolysis begins, the gas is thus formed in the midst of the active material of the plates. Until all the lead sulfate has been decomposed, part of the current goes into the charging reaction and part goes into electrolysis. When all sulfate has been decomposed, the charge is complete and all further current must cause electrolysis. The escape of the resulting hydrogen and oxygen bubbles is called gassing. These bubbles must escape through the pores of the active material. In doing so, especially at a high rate and at a high temperature, they loosen particles of active material which tend to "shed" or drop to the bottom of the cell as sediment. The capacity of the cell is proportionally reduced, and when the sediment pile grows high enough it may short circuit the plates. The mixture of hydrogen and oxygen creates an explosion hazard. As the bubbles leave the cell they entrain particles of electrolyte which lower cell capacity and corrode ventilation ducting. The energy which goes into electrolysis causes a drop in efficiency. In short, except for mixing the electrolyte, gassing performs no useful purpose and should be minimized. Reduction of gassing leads to safer, more economical operation and longer cell life.

Dacos [3, page 15] explains the reduction of gassing which he obtained as follows:

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Moore [3, page 15] explains the reduction of gassing which is obtained as follows:

.... this reduction in volume of gas comes from the fact that during a charge under pulsating voltage, the voltage is, during a fraction θ of a half-period, greater than the equivalent mean steady current, and during the rest of the half period, smaller. But, during the latter interval of time, gas stops being evolved while the voltage of decomposition [of water] is not reached, and the ions which have just reached the reacting strata of the active material enter into chemical reaction with the lead sulfate.

Since he investigated only one frequency, Dacos did not consider the effect of changing the duration of his "fraction θ". There is no obvious reason why a long non-gassing period should cause more reaction than several short non-gassing periods, although the higher ampere-hour efficiencies noted at low frequencies suggest that this is the case. Solution of this question would require a study using physical chemistry methods. Some of the obvious factors are geometry of the plates, porosity of the active material, temperature, specific gravity, and viscosity of the electrolyte, velocity of ions and gas bubbles, pressure, and current density. In Dacos' opinion,

The behavior of the cell depends essentially on the phenomenon of diffusion.

An investigation of this nature was out of the scope of the experiment.

Vinal's voltage equation, together with the observed variation of voltage ripple, sheds some light on the matter. A step increase of charging current from 0 to 4.8 amperes did not produce a step change in cell voltage, as seen in Figures 6 and 9. With the current level at a constant 4.8 amperes, the voltage gradually approached a maximum. The change in voltage must have been due to a change in one or more of the quantities r, T, and ionic concentrations. It is known that r is not constant and is a function at least of current and condition of charge. In fact Vinal

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Since he investigated only one frequency, Bouet did not consider the effect of changing the duration of his "fraction θ". There is no obvious reason why a long non-gassing period should cause more reaction than several short non-gassing periods, although the higher ampere-hour efficiencies noted at low frequencies suggest that this is the case. Solution of this question would require a study using physical chemistry methods. Some of the obvious factors are porosity of the plates, porosity of the active material, temperature, specific gravity, and viscosity of the electrolyte, velocity of ions and gas bubbles, pressure, and current density. In Bouet's opinion,

> The behavior of the cell depends essentially on the phenomena of diffusion.

An investigation of this nature was out of the scope of the experiment.

Vinal's voltage equation, together with the observed variation of voltage ripple, sheds some light on the matter. A step increase of charging current from 2 to 4.8 amperes did not produce a step change in cell voltage, as seen in Figures 5 and 7. With the current level at a constant 4.8 amperes, the voltage gradually approached a maximum. The change in voltage must have been due to a change in one or more of the quantities e, T, and ionic concentrations. It is known that e is not constant and is a function at least of current and condition of charge. In fact Vinal

[12, page 34] states that cell resistance is only a quantity which must be added to $R_{external}$ to satisfy the equations $I = \frac{V_{cell}}{R_{external} + r}$.

Furthermore he states that the ionic concentrations cannot be measured directly. "T" could hardly be considered to vary significantly under a current pulsing as rapidly as once or twice a second. Therefore the variations in performance might be linked to variations in cell resistance or ionic concentrations. One difficulty with this hypothesis is the constancy of voltage ripple above 2 cycles. Battery performance was not constant over this range.

Although voltage ripple was not measured at frequencies below 0.2 cycles per second, it is possible to predict that it will approach a maximum on the order of 0.25 for frequencies on the order of 20 minutes per cycle for a square wave of 10 minutes at 4.8 amperes and 10 minutes at zero current. This value was computed by noting that the voltage of a fully charged cell drops from about 2.8 to about 2.2 volts within 10 minutes after a charging current of 4.8 amperes is open-circuited. If performance is best at highest voltage ripple, the optimum frequency would then be on the order of 20 to 30 minutes per cycle. (The electroplating industry uses "PR" cycles on the order of 15 seconds plate and 5 seconds deplate.) A minimum practical frequency would be set by excessive shedding that would probably be caused if peak current were maintained for a matter of minutes, even if followed by an open circuit period of equal duration. For example, the prescribed finishing rate for the Willard ER-24-2 cell is 2.4 amperes. Suppose that a "pulsating" current of 4.8 amperes for 30 minutes followed by open circuit for 30 minutes, etc., were used for the finishing rate.

Although the average current would be 2.4 amperes, excessive gassing would undoubtedly occur during the 30 minute "on" period with loss of active material through shedding. The same considerations would prohibit a pulse shape such as 24 amperes for one second followed by open circuit for 9 seconds. Although average current would be 2.4 amperes, excessive gassing and shedding would again result. Cell life could probably be reckoned in pulses rather than in months. For optimum results, three conflicting requirements evidently must be balanced:

(1) a large voltage ripple;

(2) a period long enough to produce a large ripple but not so long as to produce damaging gassing; and

(3) not too high a peak current.

An educated guess is that the best frequency would be in the vicinity of 0.01 cycles per second (period of 100 seconds).

Dacos did not observe recombination of hydrogen and oxygen during the gassing period; he collected almost exactly the volume predicted by Faraday's Laws. In the present experiment only 62% of the predicted volume was actually collected; the other 38% recombined into water before escaping from the electrolyte. The Willard non-spill cells contained highly absorbent separators which undoubtedly affected the rate of diffusion and gas escape. Dacos' cells, 42 ampere-hour Tudor type BVM 3, probably contained conventional separators which left a considerable volume of electrolyte unabsorbed. Recombination of the gas can possibly be related to this difference in construction.

Although the average current would be 0.4 ampere, excessive gassing would undoubtedly occur during the 60 minute "on" period with loss of active material through shedding. The same considerations would prohibit a pulse shape such as 20 amperes for one second followed by open circuit for 49 seconds. Although average current would be 2.0 amperes, excessive gassing and shedding would again result. Cell life would probably be reckoned in pulses rather than in months. For optimum results, three conflicting requirements evidently must be balanced:

(1) a large voltage ripple;

(2) a period long enough to produce a large ripple but not so long as to produce damaging gassing; and

(3) not too high a peak current.

An educated guess is that the best frequency would be in the vicinity of 0.01 cycles per second (period of 100 seconds).

Jones did not observe recombination of hydrogen and oxygen during the gassing period; he collected almost exactly the volumes predicted by Faraday's Laws. In the present experiment only 50% of the predicted volume was actually collected; the other 50% recombined into water before escaping from the electrolyte. The Willard non-spill cells contained highly absorbent separators which undoubtedly affected the rate of diffusion and gas escape. Jones' cells, 10 ampere-hour Exide type PV 3, probably contained conventional separators which left a considerable volume of electrolyte undisturbed. Recombination of the gas can possibly be related to this difference in construction.

Since Dacos observed no recombination, his reduction of gassing must have been due entirely to reducing electrolysis. The present experiment demonstrated the reverse; ampere-hour efficiency was only slightly improved by pulsing; hence electrolysis was only slightly diminished. The main cause of reduction in gassing must then have been the reaction of hydrogen and oxygen to form water. This reaction would not be explosive if it proceeded continuously, since it could then liberate energy at no higher rate than it was supplied, about 6 watts. An explosion would result, however, if the gas collected for, say, 10 minutes recombined. It would liberate energy on the order of $6 \times 600 = 3600$ watt-seconds. If it were a chain reaction occurring in 0.01 seconds, the rate of energy release would be $3600 \div 0.01 = 360{,}000$ watts or 360 kilowatts.

It is not surprising that recombination occurs; one type of primary cell utilizes the same reaction ($H_2 + \frac{1}{2}O_2 \rightarrow H_2O$) to prevent polarization of the cathode. Vinal [11, page 216 ff.] discusses the reaction at length and points out that the actual reaction is not so simple as shown above, but actually involves several intermediate reactions.

As the experiment proceeded it became evident that statistical methods would be necessary to arrive at valid conclusions from the observed data. A comparison of the first four steady current control runs (step c of the experimental program) showed a disappointing lack of reproducibility of results. Two of these four runs were under suspicion, however. In run number 6, the cathetometer telescope was inadvertently moved during the gassing period and the height of gas in the collecting bottles was there-

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It is not surprising that recombination occurs; one type of primary cell utilizes the same reaction ($H_2 + \frac{1}{2}O_2 \rightarrow H_2O$) to prevent polarization of the cathode. Vinal [11, page 214 ff.] discusses the reaction at length and points out that the actual reaction is not so simple as shown above, but actually involves several intermediate reactions.

As the experiment proceeded it became evident that statistical methods would be necessary to arrive at valid conclusions from the observed data. A comparison of the first four steady current control runs (step 4 of the experimental program) showed a disappointing lack of reproducibility of results. One of these four runs [illegible], however. In run number 5, the [illegible] was [illegible] during the [illegible] and the [illegible] of gas in the collecting bottles was three-

fore not accurately measurable. An estimate was made, and the gas evolution computed subject to later acceptance. There was no reason to suspect the duration of charge, ampere-hours, watt-hours, or efficiencies, since the variables involved in those quantities were accurately measured.

Run number 12 was also suspected because the cell voltages on discharge dropped below the low voltage level for that rate. The charging portion of the cycle was completed, nevertheless, and the indices of performance computed. As anticipated, some of the indices differed considerably from those obtained previously.

At this point the investigators considered the advisability of neglecting the dubious results computed in cycles 6 and 12. Since their omission would tend to accentuate the difference between pulsating and steady current performance, the investigators approached the decision with conflicting emotions. On the one hand, there was excellent reason to believe the data to be extraneous. On the other hand, neglecting them would open the investigators to the charge of shutting their eyes to those data which did not confirm their theory. They consequently deferred a decision until a third series of cycles could be run. Unfortunately time did not permit the running of a number of cycles identical to the previous control runs. Instead they conducted 5 similar cycles in which the batteries were discharged at the same rate as before but for a shorter time, 10 minutes instead of 48 minutes. The cells were then charged with a constant, steady current of 2.4 amperes. Data were collected in the same way as before. The means and standard deviations of the various indices of performance were computed.

The assumption seemed reasonable that the second set of control runs should show the same spread of data as the first set. For example, if ampere-hour efficiencies for the second run fell between 80% and 85%, they could be expected to fall within a similar range for the first run. In statistical terminology, it was assumed that the first set of runs comprised a sample from a population having a certain mean and standard deviation. The second set of runs were assumed to comprise a sample of a second population having a different mean but the same standard deviation.

Hoel [6] and Wilks [13], in their discussions of small sample techniques, describe a test for the compatibility of variances. It involves the "F" distribution tabulated by Fisher and Yates [4, table V]. Briefly, the investigators followed this procedure:

1. The first two steady current control runs, numbers 1 and 7, were assumed to be random samples from normally distributed population A having mean μ_A and standard deviation σ_A; the second set of five, from normally distributed population B having mean μ_B and standard deviation σ_B.

2. It was assumed that $\mu_A \neq \mu_B$, but $\sigma_A = \sigma_B$.

3. An hypothesis H was then made that the dubious runs, numbers 6 and 12, also came from population A.

4. Under hypothesis H, the standard deviation S_A of the first four control runs should be compatible with the standard deviation S_B of the second five runs. This hypothesis was tested by forming the ratio

$F = \dfrac{n_A S_A^2 (n_B - 1)}{n_B S_B^2 (n_A - 1)}$, where n = the number of observations (runs) comprising the sample. The F distribution yields the probability that F

will exceed any given number. Entry into Fisher's tables shows that, under hypothesis H, the probability that $F \geq 4.75$ is only 0.08. Noting that $F \geq 4.75$ for the indices t, V, $V/_{af}$ and $V/_{wf}$, one rejected the hypothesis H in their cases, but accepted it for Q_c, W_c, η_Q and η_w. In other words, the volume data for runs 6 and 12 was rejected because of experimental error.

5. Volume data for runs 6 and 12 were rejected, and new standard deviations S_A' computed for V, $V/_{af}$, and $V/_{wf}$. This new value S_A' was found to be compatible with S_B.

6. Even when times for runs 6 and 12 were neglected, the standard deviations of time proved incompatible. Since the curve of duration vs. frequency showed no significant variations, no further statistical analysis of this variable was made.

These computations are tabulated in Figure 12. The mean steady DC values plotted in Figure 10 represent, for time, ampere-hours, and efficiences, the results of all four control runs. For volume evolved, volume per ampere-hour, and volume per watt-hour they represent the mean only of runs 1 and 7.

The confidence limits for the means were computed by Student's distribution as described in Wilks [13] and Hoel [6.] An unbiased estimate of standard deviation was based on compatible data from the two sets of control runs.

A belated review of Dacos' conclusions showed that lack of reproducibility might have been inferred from his statement that, [3, page 17]

> In this test, taken at random from among very numerous observations ..... there is a benefit of 25% in favor of pulsating current. Recall that the mean of all the tests was 16%.

	S_A^2	S_B^2	F	$F_{92\%}$	SIGNIFICANT AT 92% CONFIDENCE LEVEL?	$S_A'^2$	F'	$F'_{92\%}$	[illegible] AT 92%?
BASED ON									
RUNS	A1, A6, A7, A12	B1 – B5				A1, A7			
n	4	5				2			
DEGREES OF FREEDOM	3	4				1			
INDEX:									
t	0.0132	0.0027	5.21	4.75	YES	0.0250	14.8	5.8	YES
Q_c	0.0384	0.008704	4.70		NO	—			
W_c	0.2330	0.05986	4.15		NO	—			
V	9,705	1,792	5.77		YES	2031	1.81	5.8	NO
V/Q_f	449.5	94.28	5.09		YES	76.2	0.77	123	NO
V/W_f	68.52	15.33	4.77		YES	11.16	[illegible]	123	NO
η_Q	1.395	4.469	3.00	5.8	NO	—			
η_W	1.399	3.316	2.22	5.8	NO	—			

FIGURE 12. COMPATIBILITY OF VARIANCES

Dacos made no explicit mention, however, of difficulty with spread of results, nor did Vinal's chapter on Tests [12, Chapter IX] warn of this pitfall. Only after considerable grief did the investigators discover what Dacos had implied: that a few large samples would have been preferable to a number of small samples.

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CHAPTER V

SUGGESTIONS FOR FURTHER INVESTIGATIONS

This experiment raised more questions in the minds of the investigators than it answered. In the first place, it failed to prove precisely which pulsing frequency and shape produce optimum performance; this basic question remains to be solved. It did reveal, however, other questions which must be answered before the solution can be found. It also emphasized related problems and suggested techniques which can simplify and improve experiments with storage batteries. Some of these points are discussed briefly in three categories:

A. Questions whose answers are essential to a solution of the basic question.

B. Questions allied to the basic question.

C. Experimental techniques.

By the "basic question" is meant, "How does battery performance vary with frequency and shape of current pulses?" The discussions below merely highlight the points raised; they are presented as raw observations to be evaluated, ignored, or disproved by subsequent investigators.

A

Questions whose answers are essential to the solution of the basic question.

1. Is storage cell performance truly reproducible experimentally? That is, can all the variables be controlled and/or measured so that identical results can be produced by maintaining identical conditions? What variables are most important?

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A

Questions whose answers are essential to the solution of the basic question.

1. Is storage cell performance truly reproducible experimentally? That is, can all the variables be controlled and/or measured so that identical results can be produced by selecting identical conditions? What variables are most important?

2. If not, is cell performance a chance variable? If it is a chance variable, is it normally distributed, or does it follow some other distribution? How many times must a given run be repeated to determine the true mean value of a particular index of performance? If the ampere-hour efficiency is determined, say 10 times, can we confidently say that the mean of this ten-fold sample equals the population mean?

3. What wave shape produces optimum performances? Is it a square wave, half sine wave, full-rectified sine wave, or pulsed field wave? What is the optimum duty cycle? (ratio of current-on time to current-off time).

4. Would periodic reversal of charging current improve performance as it has improved electroplating quality?

5. What is the optimum pulse frequency for any given cell?

6. Does pulsing produce beneficial results on cells of all sizes and constructions?

<u>B</u>

Questions allied to the basic question.

1. Does pulsed current produce less electrolysis, or does it merely cause more of the electrolytically generated hydrogen and oxygen to recombine? If the first answer is "yes", ampere-hour efficiencies should be increased. If the second answer is "yes", the volume of escaping gas should be less, while ampere-hour efficiencies would remain unchanged.

2. Can indices of performance be related analytically to pulse shape and frequency, possibly by transient analysis?

3. If a test cell consisting of two plates, widely separated, were charged with pulsating current and the gas from the respective plates collected separately, would performance be improved?

4. Is "shedding" of active material a function of total gas formed or only of that fraction of the gas which escapes without recombining into water?

C

Experimental techniques.

1. The use of recording instruments, either in addition to or in lieu of indicating instruments, would simplify the problems of recording data, computing results, and regulating charging current. Esterline Angus recording milliammeters could be connected to measure cell voltages and charging current. Several advantages would be:

a. Continuous data record, rather than only a periodic record. This feature would allow closer determination of the time of end of charge than would the constancy of two successive readings separated by a time interval.

b. Elimination of time-consuming reading and logging.

c. Quick computation of time-average values, such as voltages, by planimeter, and quick and accurate determination of time rates.

d. Elimination of need for extremely accurate current regulation. In the present experiment, current had to be maintained exactly constant to permit accurate determination of ampere-hours as the product of current and time. If ampere-hours could be determined by planimeter,

slight variations in current would be permissible.

e. The higher inertia of recording instruments would give them a better integrating characteristic than indicating instruments. The ballistic galvanometer for current metering might prove unnecessary.

2. Since individual cell performances for a given cycle were averaged, time could be saved by metering battery voltage and gas rather than individual cell values. In this way a large number of cells could be used, rather than only three, and more reproducible mean data might result.

3. The development of a recording device for volume of evolved gas would facilitate data collection.

4. Most important of all, a number of observations should be made at each frequency at which performance is to be determined accurately. Student's distribution shows that the confidence limits for a population parameter are narrowed as the number of observations is increased. Qualitatively this means that the average of the observed data for a number of runs approaches the true value as the number of runs approaches infinity. Note that the number of observations can be increased either by repeating runs or by connecting more cells in series.

5. Bearing in mind the perversity of storage batteries in failing to behave reproducibly, the investigator should heed Hoel's warning: [6, page 215]

> Too many experimenters do not seem to appreciate the obvious injunction that the time to design [statistically] an experiment is before the experiment is begun.

A study of Hoel's Chapter XII on "Statistical Design in Experiments" should assist in planning a valid and efficient experiment.

CHAPTER VI

CONCLUSION

The experiment, while it failed to produce the quantitative results hoped for, demonstrated qualitatively that battery performance is improved by charging with pulsating current. For the Willard ER-24-2 cell a frequency on the order of 0.5 to 1 cycle per second produced best results within the frequency range covered. Further investigation, utilizing the tools of statistics, is necessary to determine the reason for this improvement and to determine optimum pulse shape and frequency for this and other cells. There is reason to believe that low frequencies are superior to high frequencies. The investigators consider their time and efforts justified since their results not only supplement the meager knowledge about pulse-charging but also point the way for future study.

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APPENDIX A

EXPERIMENTAL SETUP

The experimental setup was designed to (1) permit close control of charge and discharge currents, and to provide a choice of currents for charging; (2) provide for metering or measuring charge and discharge currents, time of charge and discharge, and individual cell voltages, temperatures, and gas evolved; (3) provide protection against accidental "reverse current" discharge of the cells; and (4) provide a stable power supply, arranged for a minimum of interruptions or disturbances to the primary power source. A brief explanation of each of these provisions will indicate the methods and principles involved and will provide a clear picture of the overall setup. In the interests of completeness, a block diagram with descriptions, and an overall circuit diagram are included.

1. Current control.

Since ampere-hour meters were unavailable, constancy of current, on both charge and discharge, was essential to the outcome of the experiment. Regulation of charging current was accomplished by the use of automatic, thermal type, variable resistance, "constant current" ballast tubes, Amperite type A-10. Characteristics of these tubes are shown in Figure 13. These tubes are designed to hold current constant to ± 2%. Supplementary rheostats were provided for very fine control, permitting excellent overall maintenance of constant current.

On discharge, the voltage of the battery alone was below the minimum operating voltage of the Amperite ballast tubes, so that discharge

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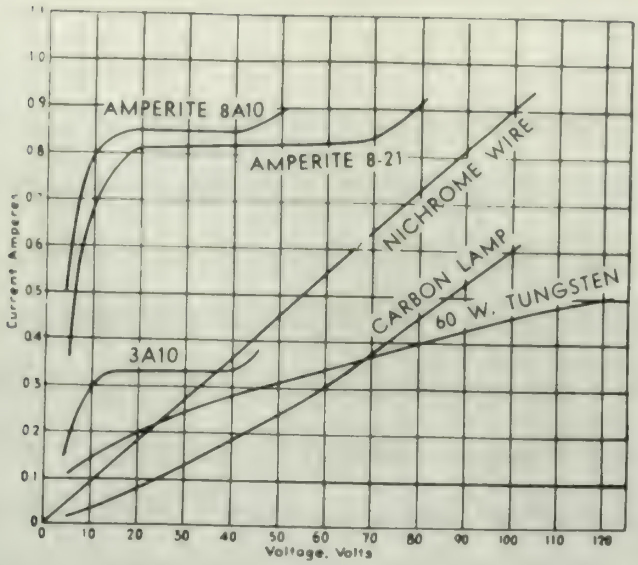
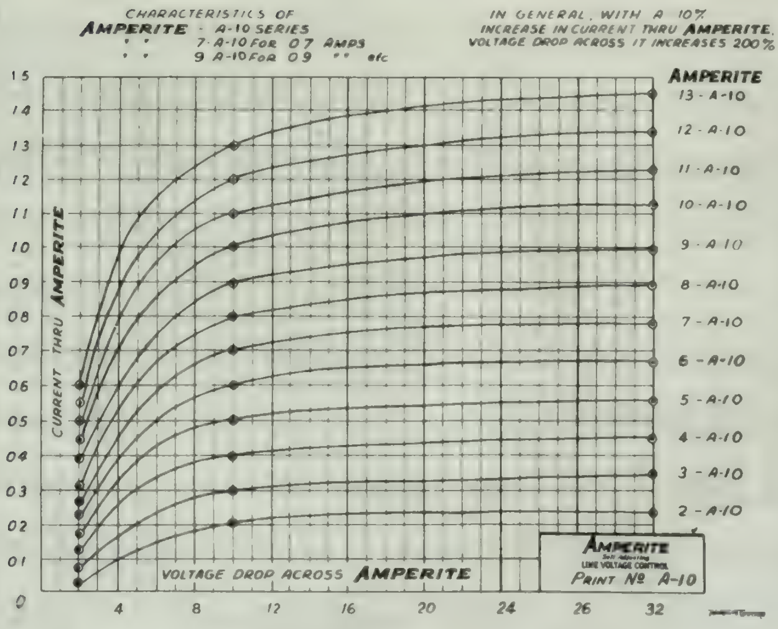
1. Current control.

Since [illegible] methods were unavailable, constancy of current, on both charge and discharge, was essential to the success of the experiment. Regulation of charging current was accomplished by the use of automatic, thermal type, variable resistance, "constant current" ballast tubes, Amperite type 4-1[illegible]. Characteristics of these tubes are shown in Figure 2[illegible]. These tubes are designed to hold current constant to ± 5%. Supplementary rheostats were provided for very fine control, permitting excellent overall maintenance of constant current.

In discharge, the voltage of the battery alone was below the minimum operating voltage of the Amperite ballast tubes, so that discharge



A. Comparison of Amperite and other resistors



B. Characteristics of A-10 series

FIGURE 13. VOLT-AMPERE CHARACTERISTICS OF AMPERITE BALLAST TUBES

current was necessarily controlled by rheostats only. Adequate control of discharge current was realized, but the rheostats required constant manipulation by the operator in order to maintain constant current.

Constant current requirements for charging included (a) a starting rate source of 6 amperes steady direct current, and for the finishing rate, (b) 2.4 amperes steady direct current, or (c) 2.4 amperes (average) pulsating direct current of square waveshape, at 4.8 amperes peak value, at frequencies from 0.5 to 8 cps, obtained from a motor driven, cam operated timer switch, or (d) 2.4 amperes pulsating direct current obtained through a half wave rectifier bank from an alternator, at frequencies from 20 to 400 cps. Of this last item, it may be said that waveshape was beyond control, since the investigators were obliged to use whatever sundry alternators that were available for this wide range of frequencies, but in any case, current was maintained at the proper average value.

2. Mensuration

The problem of metering appeared to be quite difficult at first, especially at pulsing rates below about 40 cps, where ordinary d'Arsonval movements tended to follow the current excursions rather closely, so rendering them useless for "average current" indications. In the case of current metering, when the motor driven timer switch was used, it was also necessary to consider that, although the "on" current value might be precisely 4.8 amperes, the "on" and "off" times very probably were not exactly equal*, so that the average current could not be assumed to be precise-

*This assertion was later borne out by a graphical recording of waveshape on a "Brush" recorder.

ly 2.4 amperes. Thus, a meter which would average, or integrate, was required, and a long period, ballistic galvanometer, connected to a very low resistance shunt, provided the solution. The low resistance shunt caused the instrument to be highly overdamped, thus adding to its integrating ability. An instant acting relay arrangement was provided, whereby the galvanometer and its associated shunt could be switched into either the battery charging circuit, or into a constant current reference circuit, maintained accurately at 2.40 amperes, for purposes of zero-setting and comparison.

When charging with steady direct current, or with rectified alternating current at frequencies of 40 cps and higher, ordinary d'Arsonval type ammeters were used, and provided satisfactory current indications. It is noteworthy that the precision of every electrical meter reading which might directly influence the quantitative experimental results was enhanced by the use of magnifying glasses placed over the meter scales.

Voltages were read to three decimals with a 0-3 volt scale voltmeter, provided with a switch for selecting any one cell voltage. To prevent the voltmeter pointer following the "voltage fluctuation" across the cells, during pulsing at rates below 40 cps, which would result in inaccurate voltage readings, a switching arrangement was provided so that the cells could be switched to a steady direct current charging source at 2.4 amperes for the duration of the meter readings.

While it is realized that voltages read to three decimals with an ordinary d'Arsonval voltmeter movement would be subject to suspicion

as to the absolute accuracy of the third decimal, values were nevertheless read as closely as possible, with the aid of the magnifying glass placed over the scale. The prime purpose of the voltage readings was to ascertain the point of completion of charge, based on the fact that voltage across the cell reaches a maximum at the end of charge and thereafter decreases slightly. Thus, even though the absolute magnitude of voltage may have been slightly in error, the method used enabled the operator to determine quite closely the end-of-charge point, inasmuch as the previously mentioned voltage decrease was easily discernible. It is well to note that a "set of voltage readings", as taken periodically during the finishing rate charge, consisted of three separate readings, one for each cell. In switching the voltmeter from cell to cell, its pointer momentarily swung toward zero, during the switching period, so that for each cell voltage reading, the pointer always approached its steady state position from the same direction. Any lost motion was therefore always in the same direction.

Time was reckoned by an electric timer connected to be energized automatically whenever the cells were connected to either the charge or discharge circuit.

Temperature of each cell was obtained by means of a Fahrenheit thermometer sealed into the filling cap, with the thermometer bulb immersed in the cell electrolyte.

Temperature of the evolved gas was obtained with a Centigrade thermometer inserted into the gas collecting vessel of one cell, by way

of a pilot or sample temperature determination. The investigators felt that elimination of thermometers in the other two gas collecting vessels was justified, since the three vessels were grouped closely together, and therefore subject to essentially the same changes in ambient temperature, which proved to be the major factor in determining gas temperature. Further, the two investigators were required to make 11 readings within the space of about 30 seconds every 6 minutes, so that elimination of all unnecessary readings was highly desirable.

Evolved gas from each cell displaced an equivalent volume of water from a calibrated glass vessel. The level of the remaining water in each vessel was accurately determined periodically with a cathetometer.

3. Reverse Current Protection

Inclusion of this device in the charging circuit was necessary to prevent accidental discharge of the cells through the generator armature, in the event of a power failure. The reverse current relay (Figure 14) was connected to be normally energized, through a disc rectifier; thus, the relay was energized only when current was flowing in the proper (charging) direction. Voltage to operate this relay was obtained from the IR drop across a resistance in series with the charging circuit. If, for any reason, the cells commenced to discharge through the charging circuit, the rectifier prevented current flow through the relay coil and caused the contacts to drop out. Deenergization of this relay simultaneously opened the cell circuit, stopped the electric timer clock, and shut down the motor-generator set, after which manual resetting was necessary.

of a pilot or small temperature fluctuation. The investigators felt that elimination of thermometers in the water for the collecting vessels was justified, since the three vessels were grouped closely together, and therefore subject to essentially the same changes in ambient temperature, which proved to be the major factor in determining gas temperature. Even then, the two investigators were required to make 12 readings within the space of about 30 seconds every 5 minutes, so that elimination of all unnecessary readings was highly desirable.

Evolved gas from each cell displaced an equivalent volume of water from a calibrated glass vessel. The level of the remaining water in each vessel was momentarily determined periodically with a cathetometer.

1. Reverse Current Protection

Inclusion of this device in the charging circuit was necessary to prevent accidental discharge of the cells through the generator armature, in the event of a power failure. The reverse current relay (Figure 14) was connected to be normally energized, through a diode rectifier; thus, the relay was energized only when current was flowing in the proper (charging) direction. Voltage to operate this relay was obtained from the IR drop across a resistance in series with the charging circuit. If, for any reason, the cells attempted to discharge through the charging circuit, the resulting reversed current flow through the relay coil and caused the contacts to drop out. De-energization of this relay simultaneously opened the cell circuit, stopped the electric timer clock, and shut down the motor-generator set, after which manual resetting was necessary.

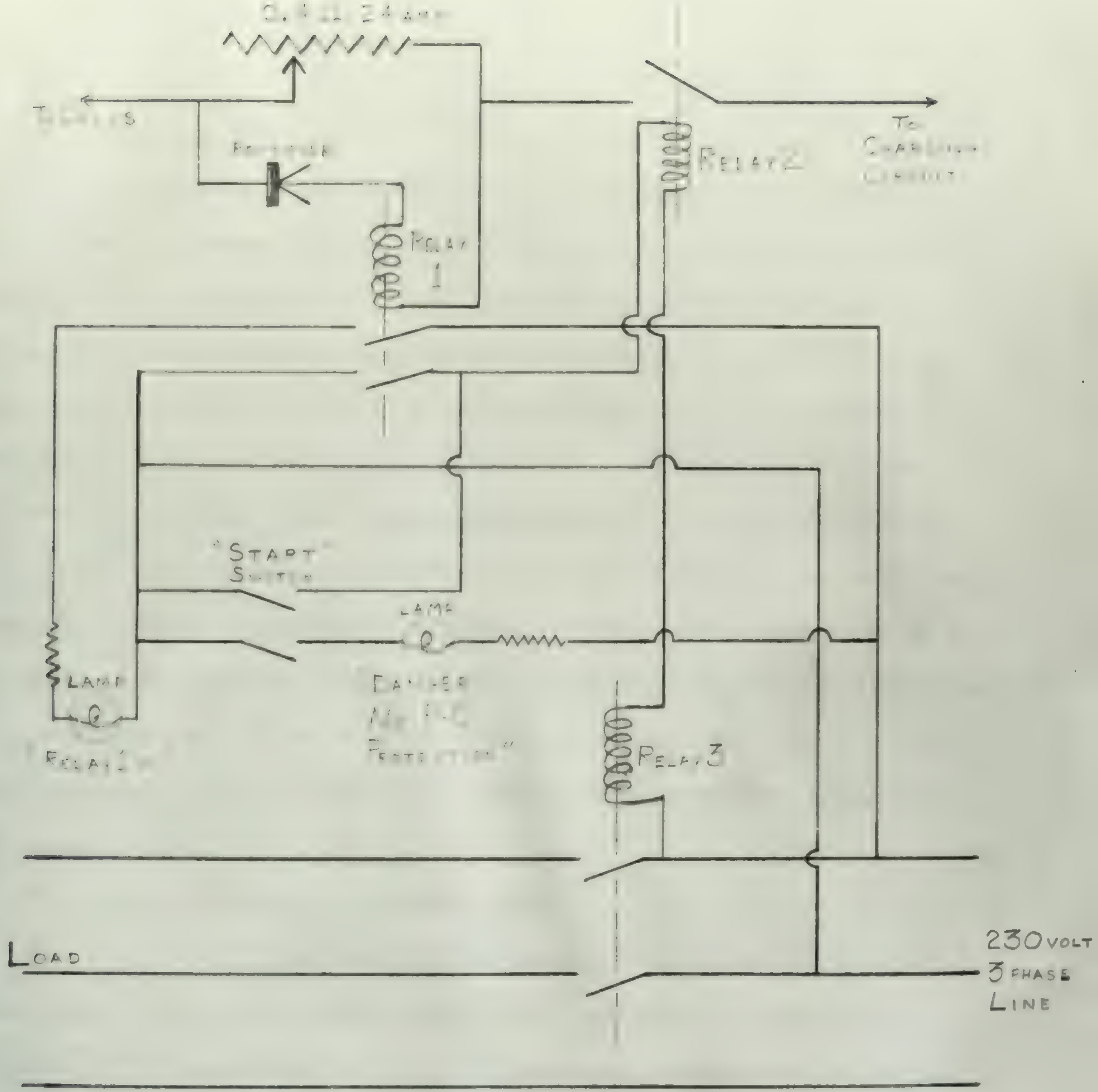


Figure 14. Reverse current relay detail.

4. Power Supply

In order to insure a minimum of interruptions or disturbances to the charging current and auxiliary apparatus (clock, motor driven timer switch, etc.), a primary power source of high capacity was desired. The system used was the largest capacity system available in the laboratory, viz., the 230 volts, 3 phase, a. c. distribution system. A transformer provided 115 volts, single phase, where needed. An oversized motor-generator set provided a stable source of charging current. This source sufficed for both the steady charging currents and the 0.5 to 8 cps pulsating direct current for charging. Alternating current for charging, from 20 to 100 cps, was supplied by a motor driven alternator, with the motor connected to a "Ward-Leonard" generator system for speed control. 400 cps alternating current was obtained from a 1.8 KVA voltage regulated, motor driven, 400 cps alternator.

5. Detailed Description of Components

The overall provisions of the experimental setup have been set forth above, followed by several explanatory paragraphs on the salient features of the apparatus. A detailed, functional description of component parts follows.

Referring to Figure 15, note that three basic arrangements of the apparatus were required. Figure 15A shows the arrangement where only steady direct current was required for charging. This arrangement was employed for the starting rate charge during every cycle, and for the finishing rate charge during the control cycles (q.v.), and was the basic arrangement, to

which modifications were made as necessary for pulsating charges, as shown in Figure 15B and C.

The generator was a 2 KW, 32 volt, 62.5 ampere machine, driven by a 15 HP induction motor, and sufficient in capacity to show negligible regulation under the relatively light charging load. Some ripple of 540 cps was discernible in the output of this machine, but the percentage of ripple voltage was negligibly small.

Two parallel connected rheostats were employed, supplementary to the current regulating ballast tubes, as previously described. Rheostat values were 4 ohms and 25 ohms, the former serving as a coarse control, the latter as a fine control.

The voltmeter arrangement for metering individual cell voltages was described above. Switch details are shown in Figure 16. Separate leads were run from the terminals of this switch direct to the actual terminals of each cell, rather than to the "battery" terminals, to eliminate any IR drop inherent in the latter terminals, by virtue of their carrying either charge or discharge current.

The reverse current protective device and the bank of Amperite current regulating tubes were previously described in this appendix. Of the Amperite ballast tubes it is worth saying that they were procured in three sizes, viz., 2-A-10, 5-A-10, and 9-A-10, having nominal current ratings of 0.2, 0.5, and 0.9 amperes, respectively. Suitable combinations of these tubes in parallel gave the various desired charging current values.

In Figure 15B, the galvanometer current metering circuit, a cur-

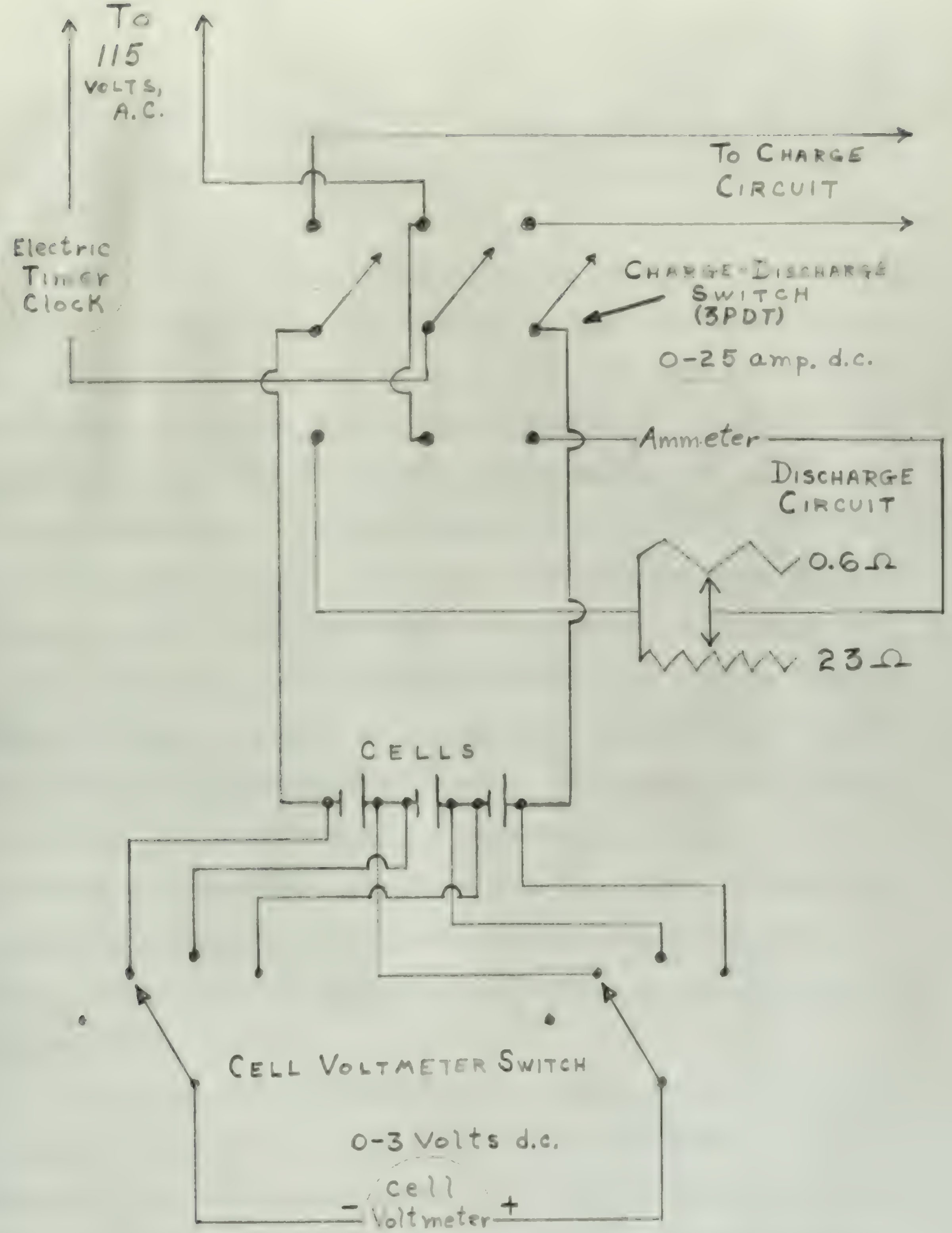


Figure 16. Cell voltmeter switch detail.

rent selector switch, a motor driven, cam operated pulser, or timer switch, an additional bank of Amperite tubes, and additional rheostats have been added.

The galvanometer circuit detail is shown in Figure 17. The galvanometer and its purpose have been described earlier. The associated relay was controlled from the galvanometer position, and permitted switching of the galvanometer from the cell charging circuit to the reference current circuit, while maintaining continuity of these circuits. The reference current circuit consisted of a source of direct current at 250 volts (obtained from a 5 KW generator, tandem coupled to the main induction motor and 32 volt generator set), a 2.4 ampere bank of Amperite tubes, a 0-3 ampere ammeter, two parallel connected rheostats of about 25 ohms each, and sufficient series resistors to limit the current to the desired value. Current in this circuit was maintained at 2.4 amperes. The galvanometer scale was not calibrated in amperes. Rather, the pointer was set to give zero deflection when the galvanometer was connected in the reference current circuit; then the galvanometer was switched into the charging circuit, and charging current adjusted to again give zero deflection, corresponding to 2.4 amperes average current.

The current selector switch, shown in detail in Figure 18, enabled the operator, in one switching operation, to choose 2.4 amperes of (1) steady current, or (2) pulsating current, at a frequency generated by and preset in the motor driven timer switch. The purpose of the steady current source was described under "Mensuration".

The heart of the low frequency, pulsating current generating device was the motor driven, cam operated timer switch shown in Figure 19.

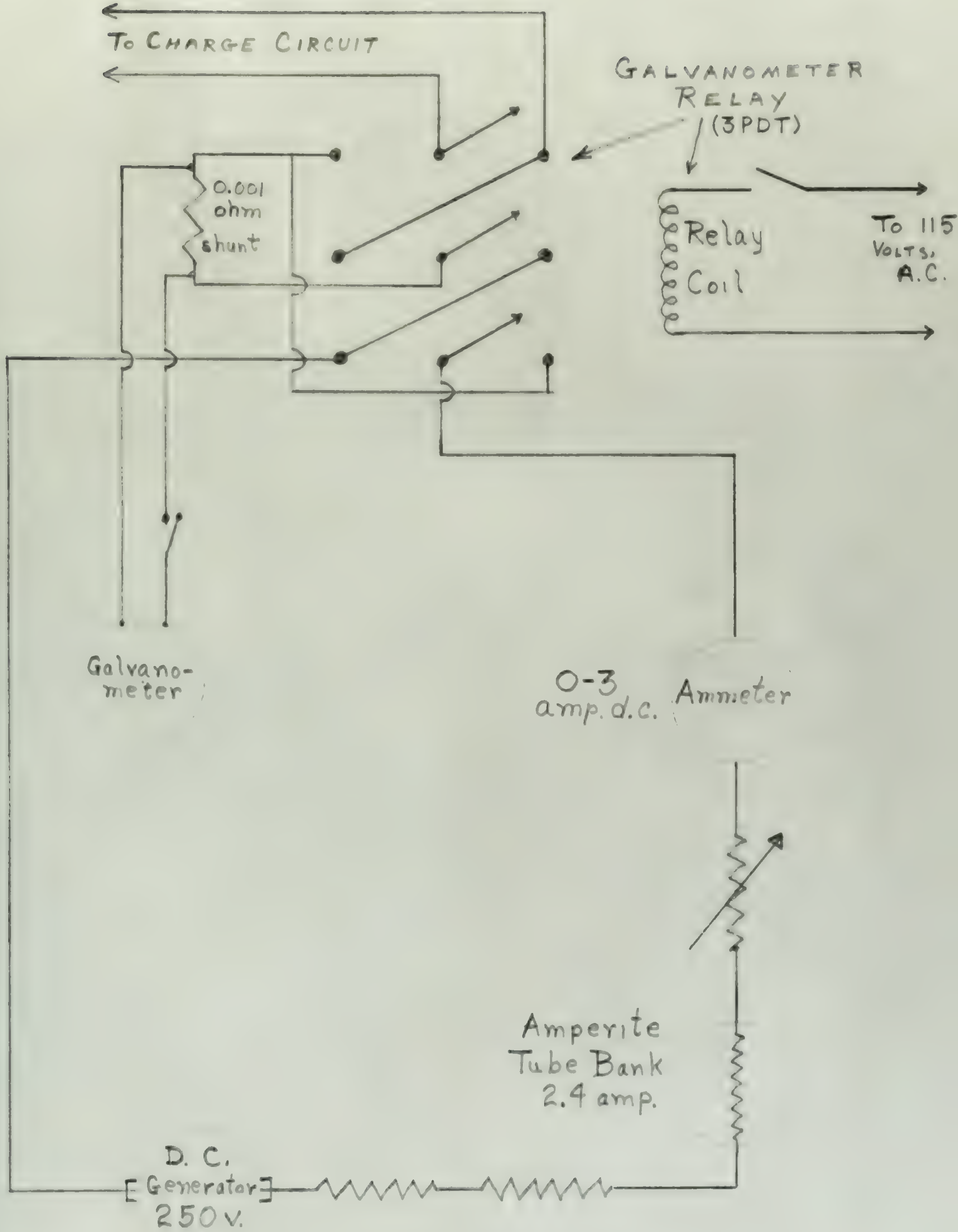


Figure 17. Galvanometer circuit detail.

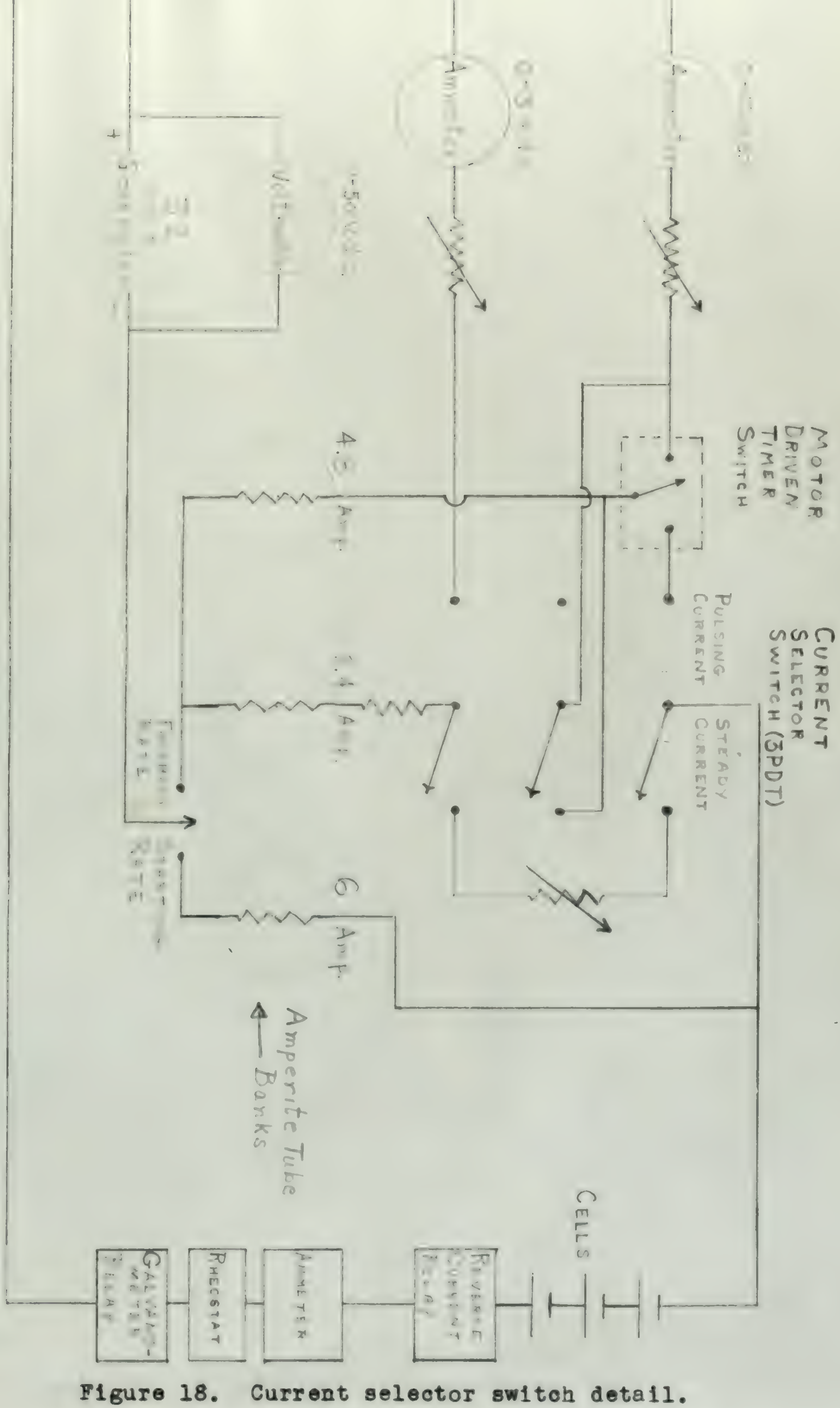


Figure 18. Current selector switch detail.

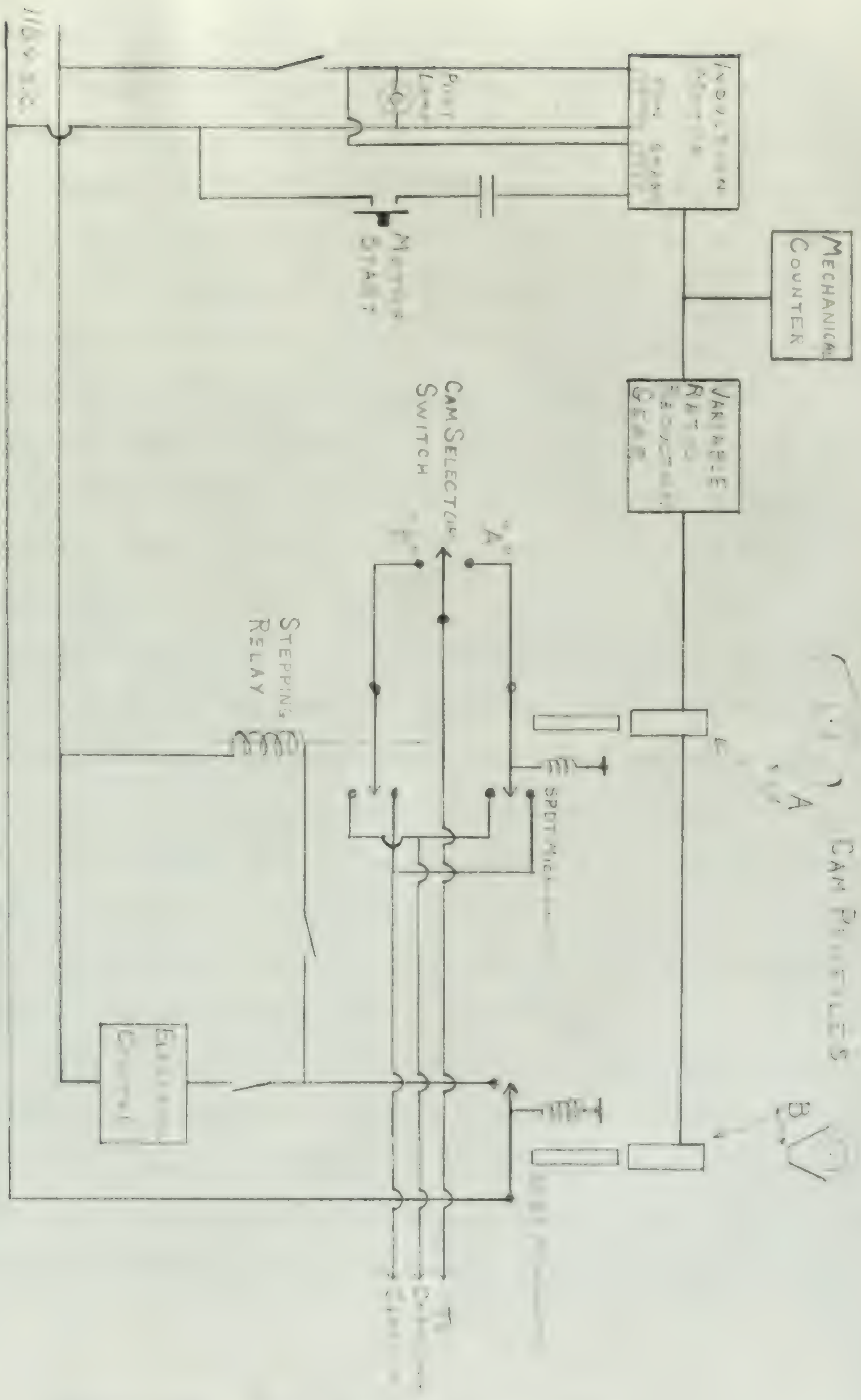


Figure 19. Motor driven timer switch.

Comprising this was a fractional horsepower induction motor driving a simple cam through a variable ratio gear train. The cam actuated a microswitch once during each revolution. The microswitch in turn energized the coil of a locking type stepping relay, with single pole, double throw contacts. The stepping relay construction was such that its contacts threw to one position or the other with each energization of the coil, and remained locked in that position until a subsequent energization of the coil. In one position the circuit to the cells was completed through the 4.8 ampere Amperite bank. In the other, the cell circuit was opened, and the Amperite tubes were switched to a rheostat and ammeter, leading back to the generator. Thus, the cells alternately received either 4.8 amperes or no current, giving an average current of 2.4 amperes, as required. The speed range of the cam permitted a pulsating current frequency range of about 0.2 to 5 cps. It was discovered that the stepping relay arrangement was unsuitable for frequencies above about 2 cps, however, so that for the runs at 3 and 7.8 cps, an additional microswitch and cam were installed, the microswitch, with single pole, double throw contacts, being substituted circuit-wise for the contacts of the stepping relay. The cam operated this microswitch every 180° of rotation, extending the frequency range of the device to an upper limit of about 10 cps.

The resistance of an Amperite ballast tube varies with temperature in much the same manner as does that of an ordinary incandescent lamp, except that the thermal time constant of the Amperite tube is longer. Due to this thermal characteristic of the Amperite tubes, it was found necessary to cause the desired value of current to flow through them continuously in

order to realize optimum current regulation. Thus, the 4.8 ampere bank of Amperite tubes was switched alternately from the cells to the previously mentioned rheostat and ammeter circuit back to the generator, the rheostat being adjusted to give an ammeter reading of 4.8 amperes, so that 4.8 amperes flowed through these Amperite tubes continuously. A similar arrangement was provided for the 2.4 ampere bank of Amperite tubes, used for obtaining steady current for purposes of voltage metering. The current selector switch connected this bank either into the cell circuit, or to a rheostat and ammeter circuit returning to the generator. Whenever the 2.4 ampere circuit was switched to the cells for a voltage reading, the motor driven timer switch contacts were short circuited, so that for this position of the current selector switch, the associated 4.8 ampere bank of ballast tubes was continuously connected to its rheostat and ammeter return circuit, independent of the timer switch.

In Figure 15C, the variable frequency alternator, thyratron rectifier bank, and associated Amperite tube bank have replaced the motor driven timer switch of Figure 15B, with other features remaining essentially the same. At frequencies of 40 cps and greater it was unnecessary to use the galvanometer for metering of current, since ordinary d'Arsonval type meters gave satisfactory results at these frequencies. Three General Electric type FG-95 thyratron tubes connected in parallel were used to half-wave rectify the alternator output. No attempt was made to utilize the unique characteristics of the thyratron tubes. Indeed, any rectifier of suitable current carrying capability would have served the purpose. The one outstanding advantage of the particular thyratrons employed was their immediate availa-

order to realize [illegible] current regulation. Thus, the 4.5 ampere bank of Amperite tubes was switched alternately from the cells to the previously mentioned rheostat and ammeter circuit back to the generator, the rheostat being adjusted to give an ammeter reading of 4.5 amperes, so that 4.5 amperes flowed through these Amperite tubes continuously). A similar arrangement was provided for the 2.5 ampere bank of Amperite tubes, used for obtaining steady current for purposes of voltage reading. The current selector switch connected this bank either into the cell circuit, or to a rheostat and ammeter circuit returning to the generator. Whenever the 2.5 ampere circuit was switched to the cells for a voltage reading, the motor driven timer switch contacts were short circuited, so that for this position of the current selector switch, the associated 4.5 ampere bank of ballast tubes was continuously connected to its rheostat and ammeter return circuit, independent of the timer switch.

In Figure 13C, the variable frequency alternator, thyratron rectifier tube, and associated Amperite tube bank have replaced the motor driven timer switch of Figure 13B, with other features remaining essentially the same. At frequencies of 60 cps and greater it was unnecessary to use the [illegible] for recording of current, since ordinary d'Arsonval type meters gave satisfactory results at these frequencies. Three General Electric type FG-[illegible] thyratron tubes connected in parallel were used to half-wave rectify the alternator output. No attempt was made to utilize the voltage characteristics of the thyratron tubes. Indeed, any rectifier of suitable current carrying capability would have served the purpose. The one outstanding advantage of the particular thyratrons employed was their immediate availa-

bility to the investigators. At the frequencies involved here (20 cps and above) it was found unnecessary to consider the thermal delay inherent in the Amperite tubes, and no auxiliary switching arrangement was provided for the purpose.

6. Gas Collecting Apparatus

The gas collecting apparatus consisted of 3 one gallon, round glass jugs, one connected to each cell and, through a pressure equalizing flask, to an over-flow reservoir, by rubber tubing, as shown in Figure 20. Gas from a cell displaced an equal volume of water from its associated jug. Pressure within each jug was reduced to atmospheric prior to each reading, by matching the water levels of the jug and its equalizing flask. Height of liquid in the jug was read to 0.01 cm with a cathetometer. Cross sectional areas of the jugs were sufficiently linear over the operating range to permit the use of a constant term in computing volume of water displaced, as, for example, 200 cc per cm. Gas volume was temperature corrected to 27° C.

bility to the investigators. At the frequencies involved here (20 cps and above) it was found unnecessary to consider the thermal delay inherent in the Amperite tubes, and no auxiliary switching arrangement was provided for the purpose.

6. Gas Collecting Apparatus

The gas collecting apparatus consisted of 3 one gallon, round glass jugs, one connected to each cell and, through a pressure equalizing flask, to an over-flow reservoir, by rubber tubing, as shown in Figure 20. Gas from a cell displaced an equal volume of water from its associated jug. Pressure within each jug was reduced to atmospheric prior to each reading, by matching the water levels of the jug and its equalizing flask. Weight of liquid in the jug was read to 0.01 cm with a cathetometer. Cross sectional areas of the jugs were sufficiently linear over the operating range to permit the use of a constant term in computing volume of water displaced, as, for example, 200 cc per cm. Gas volume was temperature corrected to 27° C.

bility to the investigators. At the frequencies involved here (20 cm and above) it was found unnecessary to consider the inverse delay inherent in the Amperite tubes, and no auxiliary switching arrangement was provided for the purpose.

5. The Collecting Apparatus

The gas collecting apparatus consisted of 5 one gallon, round glass jugs, one connected to each cell end, through a pressure equalizing flask, to an over-flow reservoir, by rubber tubing, as shown in Figure 20. Gas from a cell displaced an equal volume of water from its [illegible] [illegible]. Pressure of [illegible] [illegible] jug was reduced to atmospheric prior to each reading, by matching the water levels of the jug and its equalizing flask. Height of liquid in the jug was read to [illegible] cm with a [illegible]. Cross-sectional areas of the jugs were sufficiently linear over the operating range to permit the use of a constant term in computing volume of water displaced, i.e., for example, [illegible] cc per cm. Gas volume was temperature corrected to 37° C.

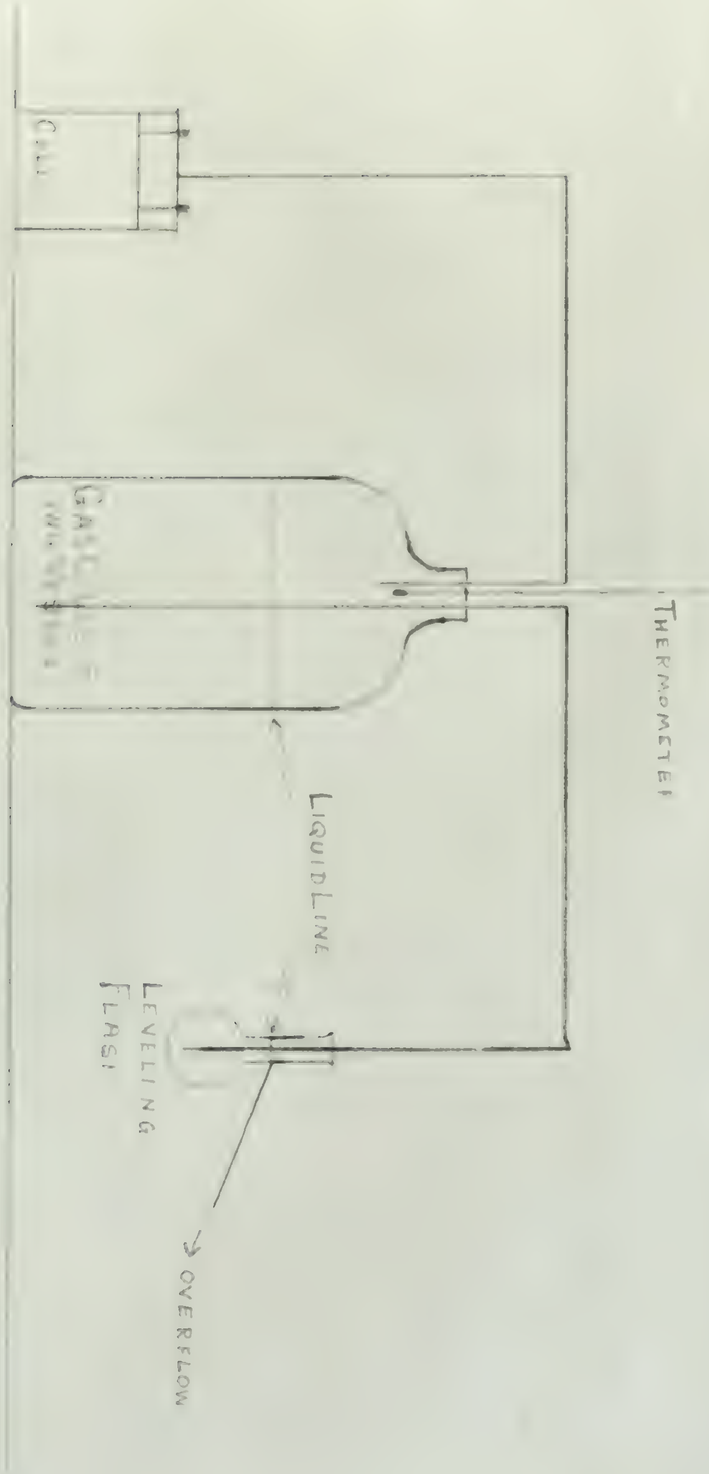


Figure 20. Gas collecting apparatus.

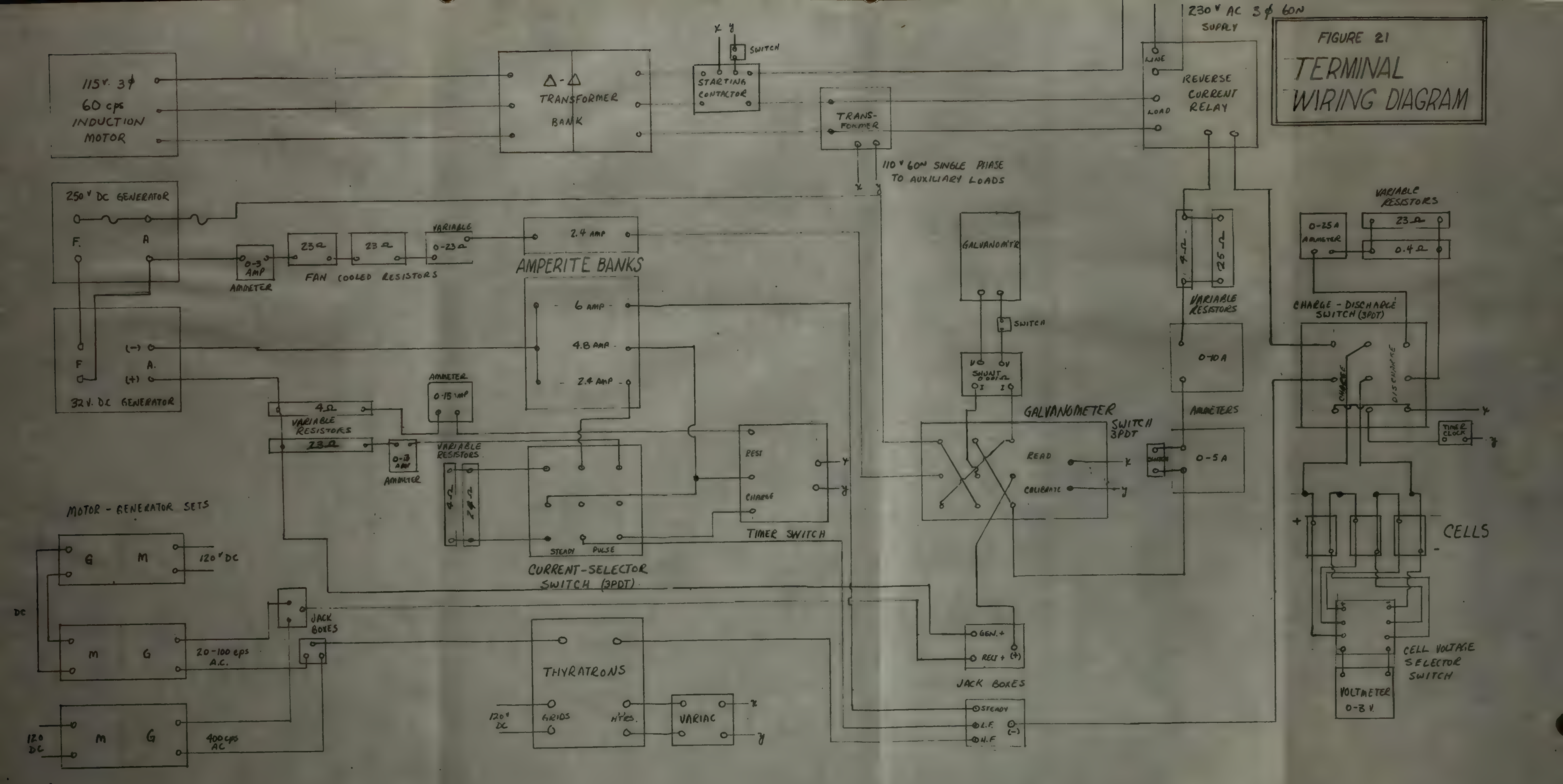


FIGURE 21
TERMINAL
WIRING DIAGRAM

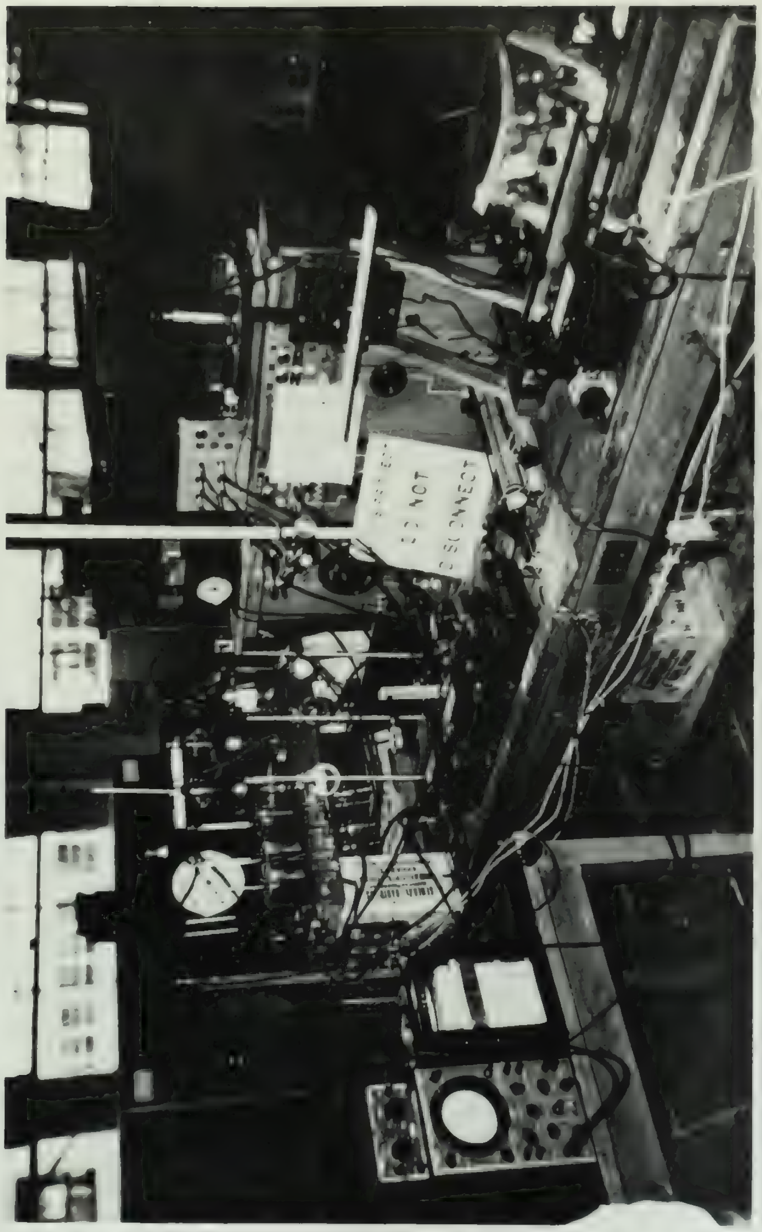


Figure 22-A. View of setup.

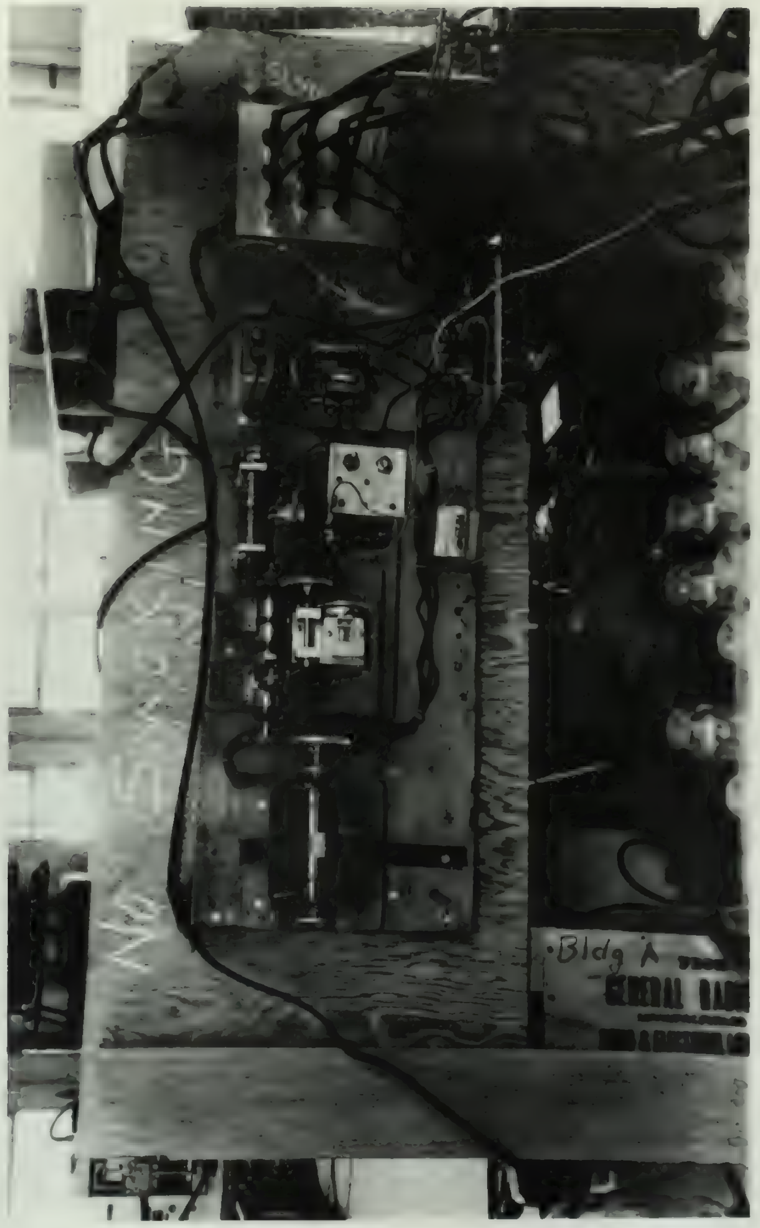


Figure 22-B. View of motor driven timer switch.

Figure 22-C. View of Amperite banks and motor-generator set.

APPENDIX B

SAMPLE CYCLE ANALYSIS SHEET

Discharge

Current (I_d) -	Constant at 15 amperes throughout discharge.
Mean Voltage (V_{md})-	Time weighted mean voltage, from voltage readings made every 6 minutes throughout discharge.
Duration (t_d) -	Duration of discharge in hours.
Ampere-hours (Q_d) -	Product of I_d and t_d.
Energy (W_d) -	Product of I_d, V_{md} and t_d.

Charge - Starting Rate

Current (I_s) -	Constant at 6.02 amperes throughout starting rate charge.
Mean Voltage (V_{ms})-	Time weighted mean voltage, from voltage readings made every 12 minutes throughout starting rate charge.
Duration (t_s) -	Duration of starting rate charge in hours.
Ampere-hours (Q_s) -	Product of I_s and t_s.
Energy (W_s) -	Product of I_s, V_{ms} and t_s.

Charge - Finishing Rate

Current (I_f) -	Constant average value throughout finishing rate charge.
Mean Voltage (V_{mf})-	Time weighted mean voltage of finishing rate charge.
Duration (t_f) -	Duration of finishing rate charge in hours.
Ampere-hours (Q_f) -	Product of I_f and t_f.
Energy (W_f) -	Product of I_f, V_{mf} and t_f.

Gas

Height (h) -	Difference in height in centimeters of water in gas collecting vessel at beginning of finishing rate charge and end of finishing rate charge.
Area (A) -	Cross sectional area of gas collecting vessel in square centimeters.
Volume (V') -	Volume of water displaced from gas collecting vessel during finishing rate charge - product of A and h.
Temperature (T) -	Gas temperature at end of finishing rate charge, °C.
Volume (V) -	V' corrected for T to a datum of 27°C, or 300° Kelvin (Centigrade, absolute).

Volume of gas per ampere-hour of finishing rate charge.	- V/Q_f	
Volume of gas per watt-hour of finishing rate charge.	- V/W_f	
Total ampere-hours of charge.	(Q_c)	$Q_s + Q_f$
Total watt-hours of charge.	(W_c)	$W_s + W_f$
Efficiency, ampere-hour.	(η_Q)	Q_d/Q_c
Efficiency, watt-hour	(η_W)	W_d/W_c

DATE — 2/19/53		CYCLE A-2		[illegible]	
ITEM	UNITS	11	12	13	[illegible]
I_d	AMP.	15.00 →			
V_{md}	VOLTS	1.9370	1.9344	1.9385	
t_d	HRS	0.8 →			
Q_d	AMP. HR.	12.00 →			
W_d	WATT-HR.	23.244	23.213	23.262	
I_s	AMP.	6.02 →			
V_{ms}	VOLTS	2.2434	2.2458	2.2613	
t_s	HRS	1.503 →			
Q_s	AMP-HR.	9.049 →			
W_s	WATT-HR.	20.298	20.320	20.460	
I_f	AMP.	2.397 →			
V_{mf}	VOLT	2.4570	2.4473	2.4774	
t_f	HRS	1.85	1.75	1.75	⟨3.286 = t_c⟩
Q_f	AMP-HR.	4.434	4.195	4.195	
W_f	WATT-HR.	10.894	10.266	10.393	
h	CM.	3.70	3.00	3.02	
A	CM^2	200	195	191.5	
V'	CM^3	740.00	585.00	578.33	
T	°C	26.9 →			
V	cm^3	740.25	585.19	578.52	634.65
V/Q_f	cm^3/A.H.	166.95	139.50	137.91	148.12
V/W_f	cm^3/W.H.	67.95	57.00	55.66	60.20
Q_c	AMP-HR.	13.482	13.243	13.243	13.323
W_c	WATT-HR.	31.192	30.586	30.853	30.877
η_Q	%	89.00	90.61	90.61	90.07
η_W	%	74.52	75.89	75.40	75.27

SAMPLE CALCULATION

RP-218

APPENDIX C

RAW DATA

Laboratory data sheets for all cycles are included in this appendix in chronological order. Dates, cycle numbers, and frequencies are as follows:

Frequency	Cycle Numbers	Date
0.5	A2	2/19/53
1	A4	3/2/53
3	A8	3/23/53
7.8	A11	4/1/53
20	A5	3/4/53
40	A3	2/25/53
100	A9	3/25/53
400	A10	3/26/53
Steady	A1	2/18/53
"	A6	3/5/53
"	A7	3/9/53
"	A12	4/8/53
"	B1, B2	4/28/53
"	B3, B4	4/29/53
"	B5	4/30/53

The final data sheet lists the meters and recorders used.

18 FEB 1953 1ST TEST CYCLE [illegible] STEADY CURRENT

																11	2	3
0920	Commenced stopping [illegible]				6	24 amps								vel		2.660	2.685	2.70
0931														4.[illegible]3		[illegible]	2.700	2.715
0945	Stopped charge.															2.675	2.700	2.715
				SG [illegible]	T	11 V	corr	corr [illegible]		T	12 V	corr	corr [illegible]		13 T	V	corr	corr [illegible]
0956	Open circuit			[illegible]	75	2.[illegible]26	+.001	2.[illegible]7		77	2.220	+.01	2.221		79	[illegible]	+.001	2.227
				corr														
0959	Commenced discharge			1499		2.001	+.003	2.004			1.993	+.003	1.996			[illegible]	+.003	2.003
1003						1.992	+.003	1.995			1.988	.003	1.991			1.998	+.003	2.001
1009						1.979		1.982			1.972		1.975			1.98[illegible]		1.983
1015						1.961		[illegible]			1.958		1.961			[illegible]		1.966
1021						1.940		[illegible]3			1.940		1.943			[illegible]		1.945
1027						1.92[illegible]		1.[illegible]23			1.91[illegible]		1.920			[illegible]		1.92[illegible]
1033						[illegible]		[illegible]			1.8[illegible]		.897			1.896		[illegible]
1039						1.861		1.86[illegible]			[illegible]		.863			1.86[illegible]		1.863
1045	Stopped charge				79	1.817	+.004	1.82[illegible]		82	1.8[illegible]		1.82[illegible]		83.5	1.81[illegible]		1.815
									2				3			Mean		[illegible]
1045	Commenced charge		I	T	V	G		T	V	G		T	V	G			[illegible]	25.62
1048			5.98	79	2.115			82	2.115	—		83.5	2.125	—			[illegible]	24.75
1100	[illegible]		6.00		2.1[illegible]				2.100				2.[illegible]75				[illegible]	0.77
1112			6.00		2.192				2.19[illegible]				2.207				[illegible]	25.7[illegible]
1124			6.00		2.217				2.2[illegible]				2.230				[illegible]	24.9[illegible]
1136			6.00		2.2[illegible]				2.246				2.254				Δ	[illegible]
1148			6.00		2.260				2.260				2.278				[illegible]	25.13
1200			6.00	83	2.288			86	2.2[illegible]			87	2.30[illegible]				[illegible]	24.96
																	Δ	0.97

18 Feb 1953 1st test cycle charge

Time	Remarks		I	T	11 V	CB G		T	12 V	C1 G		T	13 V	D4 G		Temp	Mean cell temp	TVG volts
1202				83	2.320	46.32		86	2.3[illegible]	46.2[illegible]		87	2.335	46.[illegible]			75.3	2.364
120[illegible]	Reduced to		6.00		2.365				2.35[illegible]				2.364					2.36[illegible]
1205	Commenced charge rate		2.40	83	2.272	29.9[illegible]		86	2.2[illegible]	30.41		87	2.284	30.61		27.7		
1209				8[illegible]	2.2[illegible]				2.2[illegible]				2.28[illegible]					
1215			2.4[illegible]		2.[illegible]				[illegible]				[illegible]					
1241			[illegible]		[illegible]				[illegible]				2.[illegible]					
1247			2.40		2.3[illegible]				2.[illegible]				2.320					
1253			2.40		2.320				2.317				2.334					
1259			2.40		2.340				2.[illegible]				2.352					
1305			2.40		2.362				2.349				2.380					
1311			2.40		2.402				2.[illegible]				2.425					
1317			2.40		2.470				2.425				2.499					
1323			2.40		2.54[illegible]				2.484				2.580					
1329			2.40		2.5[illegible]				2.57[illegible]				2.626					
1335			[illegible]		[illegible]	26.7[illegible]			2.[illegible]	29.32			2.641	29.16		25.9		
[illegible]			2.40		2.670	28.41			2.630	28.70		[illegible]	2.670	28.70		25.[illegible]		
1347			2.40		2.621	[illegible]			2.641	27.6[illegible]			2.65[illegible]	27.5[illegible]				
[illegible]			2.40		2.6[illegible]	27.3[illegible]			[illegible]	[illegible]			2.66[illegible]	27.34				
[illegible]			2.40		2.625	27.34			2.644	28.0[illegible]			2.661	27.10		25.8		
[illegible]			2.40		[illegible]	26.61			2.649	[illegible]			[illegible]	[illegible].42		25.9		
1[illegible]55			2.40		2.63[illegible]	[illegible]			[illegible]	[illegible]			2.664	[illegible]		26.[illegible]		
[illegible]			[illegible]		[illegible]	[illegible]			2.634	[illegible]			2.6[illegible]	[illegible]		26.0		
[illegible]			2.40		[illegible]	[illegible]			2.651	23.68			2.666	28.88		26.2		
14[illegible]			[illegible]		2.631	[illegible]937			2.6[illegible]	[illegible]			2.668	[illegible]		26.3		
1429			[illegible]		[illegible]	[illegible]			[illegible]	[illegible]			[illegible]	[illegible]		26.[illegible]		
14[illegible]			2.40		2.632	23.[illegible]			2.652	23.[illegible]			2.667	24.31		26.4		
1436	Stopped charge			86				90				90.0						[illegible]

Stat at 25.62 25.71 25.86

[illegible] Test Cycle #2 [illegible] @ 15th hour [illegible]

Time	Remarks	I	T (11)	V (11)	T (12)	V (12)	T (13)	V (13)	11	12	13
[illegible]	Commenced [illegible] @ 2.4 amps							VM# 24783			
1045									2.679	2.7[illegible]	2.730
1050									2.676	2.705	2.720
[illegible]	Stopped chg										
1107	[illegible]								2.231	[illegible]	2.235
1108	Commenced discharge		T	V	T	V	T	V			
1108		.49	78	1999	79	1.987	81	2.001			[illegible]
1110		[illegible]		2.001		2.001		2.008			[illegible]
1114		[illegible]		1997		1992		2.000			[illegible]
1120		15.00		1.980		1.977		1.983			[illegible]
1126				1.962		1.959		1.965			[illegible]
1132				1.942		1.938		1.945			[illegible]
1138				1.921		[illegible]		1.922			[illegible]
[illegible]				1.902		1.87[illegible]		1.900			[illegible] 6
[illegible]				1.860		[illegible]		1.860			6
	Stopped discharge		81	1.810	83	1.813	84	1.807			Electr. vol.

11	Start	27.52
	End	26.70
	Δ	.82
12	Start	7.58
	End	6.73
	Δ	.85
13	Start	26.78
	End	7.53
	Δ	.75

Time	Remarks	I	T (11)	V (11)	G (11)	T (12)	V (12)	G (12)	T (13)	V (13)	G (13)	Gas temp	Coulometer
1200	Start charge	6	81	2.092		83	2.099		84	2.1[illegible]	–	–	–
1215		6	81	2[illegible]64		83	2168		84	2181			
1224			81.5	2192		83	2194		84	2206			
1236			81	2219		83	2220		83.5	2235			
1248			80.5	2240		83	2242		83.5	2258			

19 Feb. '53 [illegible] Cycle #2 Pulsating @ ~~[illegible]~~ (1/2 cps.)

Time	Remarks	I	T (11)	V (11)	G (11)	T (12)	V (12)	G (12)	T (13)	V (13)	G (13)	[illegible]	[illegible]
					30.46			[illegible]			30.88		
1300		6.00	80.5	2241		82.5	2263		83.5	2280			
1312				2.[illegible]14			2.297			[illegible]			
1324	Coul = 2[illegible]		[illegible]	2 319		82.5	2 332		83	2 345			
1330	Hot [illegible] Stopped chg									2 372			
1335	Resumed chg	2.40 pulse	[illegible]		33.58	82.5		33.44	83		34.16	26.8	27241
1338				2266			2265			2280			
1340				2278			22[illegible]4			2 2[illegible]			
~~1407~~													
[illegible]												[illegible]	28241
1354	Δ = [illegible]												28381
1354+													28408
1402				[illegible]			2.3[illegible]2			2317			
1414				2.325			2.323			2.340			
1426				2[illegible]			2.350			2 373			
1438				2.453			2.421			2.520			
1450				~~2.620~~ 2.580	32.10		2.510	32.72		2.620	32.35		
1456				2.595	32.40		2.619	32.40		2.635	32.17		
1502				2.609	31.91		622	31.9[illegible]		2645	32.54		
1504													32568
1508				2.618	31.47		2.629	31.54		2.653	32.14		*
1514				2.620	30.96		2.640	30.99		2.656	31.67		
1520				2.6[illegible]	30.46		*2.648	30.44	*	2.661	31.14		
1526			*	2.626	29.88		2.649	29.16		2.660	30.70	26.9	
1528													34.16
1532				2626	29.34		2648	29.24		2660	30.7	26.2	[illegible]
1538				2.626	28.79		2648	28.76		2.660	29.11	26.9	
1539													34670

Test Run # 3 - rectified 40 cps a.c. 25 Feb. 1953

Time		I	T	V	G	T	V	G	T	V	G			
0851		2.4	Commenced "topping off" charge.											
—				#11			#12			#13				
0853				2655			2685			2695				
0857				2693			2720			2738				
0900		↓		2695			2720			2738				
0902		2.4	67	2695		68.5	2720		70	2738				
—			Secured t.o. charge											
—														
0911		0		2222			2220			2231		open ckt.		
0914		0		2220			2208			2211				
0920				2200			2196			2205				
0920	Start discharge													
0920.5		14.99		1960			1960			1977				
0926		14.99		1975			1968			1979				
0932		CORR =		1958			1949			1.960				
0938		+ 0.01		1940			1932			1.940				
0944		CURRENT		1.921			[illegible]			1922				
0950		15.00		1902			1896			1902				
0956		↓		1875			1.870			1,875				
1002				1839			1834			1838				
1008			74	1781		75	1780		78	1779				
		Secured discharge												
1010	commenced starting rate charge.													
1010		6.0												
1012				2102			2098			2104				
—														
	Elect. ht.				29.43			29.44			29.36			
	Fil. line				28.59			28.56			28.64			

Test Run # 3 - rectified 40 cps a.c. 25 Feb. 1953

Time		I	T	V #1	G	T	V #2	G	T	V #3	G		Tmp	~~[illegible]~~	
1024		6.0		2166			2165			2179		Bottle	top	lits:	
1036		6.0		2200			2199			2213		4911	4922	4922	
1048		6.0		2222			2224			2240					
1100		6.0		2245			2250			2261					
1112		6.0		2268			2274			2283					FRAMA SYSTEM MIK
1124		6.0		2300			2301			2317					# 10- 12V 10 - USV - 220 HS
1136		6.0		2335			2339			2350					
1139		6.0		2343			2345			2360				↓	±1 cycle/sec
1140		0	Stopped charge											[illegible]	
1143	Start FR	2.40	83	2248	33.03	84	2250 33.07	33.07	85	2265	33.68			40	
1155		CORR:		2.270			2.273			2.285					
1207		-.003		2.283			2.288			2.300				40	
1219		Act. 2.397		2.305			2.308			2.320				40.5	
1231		↓		2.334			2.330			2.347				40.5	
1243				2.400			2.380			2.412				40	
1255				2.528	32.45		2.494	32.63		2.560	[illegible]			39.7	
1301				2.576	32.09		2.485	32.27		2.610	[illegible]		28.4	40	
1307				2.592	32.33		2609	31.84		2622	31.62		28.4	40	
1313				2.602	31.20		2.622	31.40		2.633	[illegible]				
1319				2.608	30.64		2.632	[illegible]		2.641	[illegible]		28.	40	
1325				2.612	30.13		2.638	30.28		2.644	[illegible]		[illegible]	40	
1331				2.614	29.55		2.640	29.68		2.648	[illegible]		[illegible]	40	
1337				2.616	29.01		2.640	29.12		2.650	29.47		[illegible]	40	
1343				2.615	28.46		2.640	28.50		2.652	[illegible]		[illegible]	40	
1349			91	2.615	27.73	94	2.640	27.77	95	2.650	29.02		29.0	40.5	
1355				2.614	27.27		2.638	27.28		2.648	28.55		29.1	40.0	
1401			92	2.608	26.18	95	2.637	26.85	96	2.646	28.04		29.2	40	

1406 stopped charge -

4TH TEST CYCLE 2 [illegible]

		I	T	V	A	T	V	A	T	V	A	GT	
1150	Commenced [illegible]	2.40	[illegible]	26[illegible]			1712			2 [illegible]			
1156				[illegible]			2 [illegible]			2 [illegible]			
[illegible]			72	[illegible]		73	[illegible]		75	[illegible]			
1205				2670			[illegible]			[illegible]			
[illegible]				2 [illegible]			2719			2 [illegible]			
1210				2 675			2 [illegible]			2 [illegible]			
1212				2 675									
1215	Stopped charge [illegible]			[illegible]			2.705			[illegible]			
1217		1449		1991			1 [illegible]			1 [illegible]			8
[illegible]		[illegible]		1960			1 [illegible]			1 [illegible]			5
[illegible]8				1 [illegible]			1960			1970			7.5
[illegible]6		[illegible]		1 [illegible]			1 [illegible]			1.945			5.5
[illegible]			[illegible]	1 [illegible]		[illegible]	1 [illegible]		71	1 [illegible]			4
[illegible]				1 [illegible]			1 [illegible]			1912			6
[illegible]				1 [illegible]			[illegible]			1 [illegible]			6
[illegible]				[illegible]			[illegible]			1 [illegible]			6
[illegible]	Stopped discharge		75	1 [illegible]		81	1 [illegible]		83	1 [illegible]			3
	I [illegible]												
1311	6.0			212[illegible]			2121			2132			
[illegible]	6.0			2162			2162			2179			
1325	6.0			2196			2198			2[illegible]11			
[illegible]17			[illegible]	2217		[illegible]	2220		[illegible]	2237			
1359				[illegible]			[illegible]			2251			
1412				[illegible]			[illegible]68			[illegible]			

[illegible]

T[illegible]	[illegible]	I	T	V	A	T	V	A	T	V	A	GT	
[illegible]	[illegible]	6.0	83	2 [illegible]		86	2294		87	2 [illegible]			
[illegible]	Stopped charge [illegible]	↓		2 310			[illegible]326			[illegible]			
	[illegible]												
[illegible]	[illegible]												
[illegible]	[illegible]								[illegible]	266			
1450	[illegible]	[illegible]			[illegible]			3276			[illegible]	[illegible]	[illegible]
[illegible]				[illegible]			[illegible]			[illegible]			
[illegible]													[illegible]
[illegible]													[illegible]
[illegible]													[illegible]
[illegible]				[illegible]			2 [illegible]			[illegible]			
[illegible]38.5				[illegible]			[illegible]			[illegible]			
[illegible]			[illegible]	2 [illegible]		8[illegible]	[illegible]		8[illegible]	[illegible]			
[illegible]				[illegible]			[illegible]			[illegible]			
[illegible]				[illegible]						[illegible]			
[illegible]				[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]		
[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]				[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	
[illegible]				[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]		[illegible] — [illegible]
[illegible]				2.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]			[illegible]	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	[illegible].1	
[illegible]				[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]		
[illegible]	Stopped [illegible]												

5TH Test Cycle 20 ~/sec 3/4/53

Time	Remarks	I	T	V	G	T	V	G	T	V	G		GT		
	I	5TH TEST CYCLE			20 ~/SEC			3/4/53							
0859	Commenced topping 11 @ 2.4 a.														
0901	2.4			2690			2721			2737					
0913	2.4			2703			2731			2748					
0921	Secured T.O. chg.			2703			2729			2739					
	I			11			12			13					
	12AH discharge:		T	V	G	T	V	G	T	V	G				
0926	15.0 [illegible]		73			74			77						
0927	15.0			1981			1980			1995					
0932	15.0			1987			1983			1998					
0938	↓			1972			1968			1979					
0944				1956			1948			1960					
0950				1938			1932			1940					
0956				1915			1908			1919					
1002				1890			1882			1892					
1008				1856			1847			1858					
1014	15.0 Stopped disch.		77	1801		79	1796		81	1801					
	Commenced charging @ starting rate														
1015	6.0 [illegible]		77			79			81						
1017	↓			2102			2100			2110					
1027				21[illegible]			2154			2168					
1039				[illegible]95			2196			2209					
1051				2220			2221			2237					
1103				2241			2243			2259					
Time	Remarks	I	T	V (11)	G	T	V (12)	G	T	V (13)	G		GT		
1115	[illegible]	[illegible]		22[illegible]			[illegible]70			2283					
1127		↓		2[illegible]			[illegible]301			2315					
[illegible]39				[illegible]			[illegible]			[illegible]					
[illegible]	[illegible] F.S.=13 [illegible] S.R. [illegible]														
[illegible]47	[illegible] F.R.	2.40												F[illegible]	Fr[illegible]
1149		2.4	[illegible]2	2[illegible]	35.11	84	[illegible]9	[illegible]	[illegible]5	2212	32[illegible]		29.1	403	
1200				2.280			2284			2.3[illegible]					20.5
1209	[illegible]														
1210	[illegible]														
1212		[illegible]		2[illegible]			[illegible]			23[illegible]					
1224		[illegible]	81	23[illegible]		83	2323		84	2329				40[illegible]	
[illegible]	R[illegible]														
[illegible]3	R[illegible]	2.[illegible]												2295	
[illegible]		2.4		[illegible]			[illegible]			2[illegible]					
[illegible]	[illegible] TVG								→	2365					
[illegible]	F[illegible] T														
1247	FIXED!!	2.4													
1249		2.[illegible]		2357			2[illegible]			2480				402	
1300		2.[illegible]		2468			[illegible]			2491				40[illegible]	20.5
1312		2.4		2582	[illegible]73		2588	32.13		2620	32.22		29		
1318		↓	8[illegible]	2600	31.56	8[illegible]	2620	31.70	86	2648	31.75				20.[illegible]
1324				2[illegible]	31.04		2640	31.27		2656	31.38		[illegible]		20.0
[illegible]				[illegible]4	3[illegible]		2646	30.76		2663	30.[illegible]		[illegible]		[illegible]
[illegible]				[illegible]30	30.[illegible]		[illegible]	30.[illegible]	→	2669	[illegible]		27.5		20.[illegible]
[illegible]				[illegible]32	[illegible]		2653	[illegible]		2660	[illegible]		27.6		
[illegible]				2634	28.10	→	2654	[illegible]		2666	[illegible]		27.6	[illegible]	[illegible]
[illegible]	[illegible]	2.[illegible]	8[illegible]	2632	28.44	[illegible]	26[illegible]4	28.[illegible]	9[illegible]	26[illegible]1	28.1	[illegible]	f		
[illegible]			→	2636	[illegible]		2653	28.1		2668	28.40	21.8			
[illegible]		↓		[illegible]4	[illegible]		26[illegible]	2.41		266[illegible]	[illegible]	28.[illegible]	20		
1412				[illegible]33	26[illegible]		26[illegible]	[illegible]		2661	27.40	28.0			
1413	Stopped chg.														

5 March 6th Test Cycle Steady current

		I	T	11 V	G	T	12 V	G	T	13 V	G	ΔT
1049	Commence [illegible]	2.40	77	26.2		79	2681		80	2202		
1052				[illegible]			2692			[illegible]		
1100				2.168			2693			2.205		
1106				2.667			2693			2.205		
1108				2.[illegible]			2692			[illegible]		
1109	Stop charge											
1110	Start discharge	14 99										
1111		↓	80	1993		82	1995		84	2.008		
1116				2001			1997			2006		
1122				1986			1980			1.99[illegible]		
1128				1.965			1958			1.967		
1134				1.948			1942			1952		
1140				1 92[illegible]			1920			[illegible]		
1146				1899			[illegible]92			1900		
1152				1[illegible]			18[illegible]			[illegible]		
1155	Stop [illegible]			1819			1814			1818		
1200	Commence SR	6.0	86.5			88			90			
1203		6.0		2109			2107			2119		
1212		6.0		2147			2145			2161		
1224		6.0		2183			2182			2199		
1236		[illegible]		[illegible]			[illegible]			[illegible]		
1248		[illegible]		2.2[illegible]	[illegible]		2.2[illegible]			[illegible]		
1300		[illegible]		2.[illegible]	[illegible]		[illegible]			[illegible]		
1312		6.0	86	2 279		[illegible]	2280		[illegible]	[illegible]		
1324		6.0	87	231[illegible]		89	[illegible]		[illegible]	[illegible]		

6TH CYCLE 5 March STEADY CURRENT

		I	T	11 V	G	T	12 V	G	T	13 V	G	T
1330	[illegible] Stopped [illegible]	[illegible]	87	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]		
[illegible]	Resumed charge, at [illegible] rate	2.40			32.66			33.39			33.[illegible]	
1335		2.40	3	2.260			2.[illegible]			[illegible]		[illegible]
[illegible]		↓	11	2 2 72	33.30		2.[illegible]			[illegible]		
[illegible]56			10	2.[illegible]6			[illegible]			2.[illegible]		
[illegible]			12	2 3[illegible]			2 [illegible]			2.[illegible]		
1420			12	2.335			2.33[illegible]			2 [illegible]		
1432			12	2.[illegible]			2.3[illegible]			2 [illegible]		
1444			12	2.463			2.493			2 513		
1456			12	2.572	31.75		2.593	32.51		2.612	32.15	29.9
1458	Stopped		[illegible]		?			?				
[illegible]	Resumed	2.40										
1506			[illegible]	2.58[illegible]	[illegible]		2.612	32.77		[illegible]	[illegible]	29.1
1514			[illegible]	2.60[illegible]	31.46		2.628	32.20		2 640	31.37	
1522			[illegible]	2 609	30.76		2.631	31.46		2 654	[illegible]	28.8
1528			[illegible]	2 615	30.24		2 641	30 90		2 651	[illegible]	28.8
1534			[illegible]	2.6[illegible]	[illegible]5		2.6[illegible]	[illegible]		[illegible]	[illegible]	
1540			[illegible]	2.621	29.70		2 648	29.[illegible]		2 664	[illegible]	[illegible]
1546				2.618	[illegible]		2.647	[illegible]		2.663	[illegible]	28.[illegible]
1552				2.620	28.[illegible]		2.[illegible]	[illegible]		2.[illegible]	[illegible]	28.[illegible]
1558			92	[illegible]617	[illegible]	92	[illegible]648	[illegible]	92	2.[illegible]	[illegible]	[illegible]

Note: Cathetometer was moved after reading [illegible] [illegible] Level was calculated from [illegible] [illegible].

[illegible] 33.89

Δmax 129 / 100 — -29 / 38-30 — 1.86 / 1.61 — -25 — 186 / 155 31

9 March 1953 Steady current test 7th CYCLE

Time	Remarks	I	T	11 V	G	T	12 V	G	T	13 V	G	G.T.
1047	Commenced heating	[illegible]	73	2		74			75			
[illegible]				2.633			2.665			2.672		
[illegible]				2.640			2.676			2.68[illegible]		
11[illegible]				2.652			2.680			2.699		
[illegible]				2.658			2.684			2.70[illegible]		
1111.5				2.660			2.684			2.70[illegible]		
1116			→	2.662			[illegible]690		→	2.708		
[illegible]				2.662		→	[illegible]698			[illegible]		
1127			76	2.662		[illegible]	[illegible]		81	2.717		
1129	Stopped charge											
1130	Started discharge (12 AH)	1400										
[illegible]	-10	↓		1998			1996			2004		
1136				1989			1983			1995		
1142	0002			1971			1965			1978		
[illegible]	0002			19[illegible]			1947			1959		
[illegible]	1[illegible]			1938			1930			1940		
12[illegible]	20			19[illegible]			[illegible]			[illegible]		
[illegible]	2[illegible]			18[illegible]			1887			1891		
[illegible]	3[illegible]			18[illegible]			1857			1862		
1219	[illegible]	Ended discharge		1817			1813			1818		

9 March 1953 Steady Current Test 7th cycle → [illegible] Positive Tops } 11 - 48.37, 12 - 48.45, 13 - 48.45

Elapsed Time	Time	Remarks	I	T	11 V	G	T	12 V	G	T	13 V	G	G.T.	
0	1220		6.0											
2	1222				2108			2103			2114			
6	1226		↓		213[illegible]			2129			2141			
12	1232				21[illegible]			2155			2163			
24	1249			32~~7~~2	2190	[illegible]	32~~7~~6	2189	.286	32~~7~~6	2203	[illegible]		
[illegible]	[illegible]56				2216			2218			2231			
50	1310				2.1[illegible]			[illegible]			[illegible]			
60	1320				22[illegible]			2[illegible]5			[illegible]			
1:12	[illegible]				229[illegible]			22[illegible]8			22[illegible]9			
1:2[illegible]	1344			83	2.327		86	2.332		87	2.346			TVG: 2.36 @ 87°
1:28	1348	Reached TVG stopped charge								87	2.360			
0 00	1352	Resumed 6 hr. rate	340		2.240	[illegible]		2.2[illegible]	32.89		2.26[illegible]	32.86		
0 [illegible]	14[illegible]			84	2.270		87	2.27[illegible]		88	2.286	?		
0 .4	1416				2286			2.2[illegible]			[illegible]			
0 [illegible]	142[illegible]				2305			[illegible]306			2320		29.8	
[illegible]	14[illegible]				2.328			[illegible]327			2.341			
1 [illegible]	1452				2.368			2.364			2.379			
1-12	1504				2.[illegible]			[illegible]43[illegible]			2.455			
1-1[illegible]	15[illegible]				2.570			[illegible]514			2.591		28.0	
[illegible]	[illegible]			→	2.586	31.54		2.601	[illegible]86		2.619	31.[illegible]	28.0	
[illegible]	[illegible]				2.60[illegible]	31.[illegible]		2.619	31.41		[illegible]633	314[illegible]	[illegible]	
[illegible]	15[illegible]				2.608	30.61		2627	30.7[illegible]		2.642	30.74	27.9	
1-41	15[illegible]				2.612	30.06		2634	30.42		2.64[illegible]	30.48	2[illegible].8	
1-5[illegible]					2.619	29.55		2.6[illegible]	29.90		2.652	29.97	27.7	
2 00					2.6[illegible]	28.99		2.640	29.38		2.654	29.48	27.6	
2 0[illegible]					2.620	28.45		2.641	28.83		2.651	28.93	27.6	

9 March STEADY CURRENT 7TH CYCLE

Elapsed Time	Time	Remarks	I	T	11 V	G	T	12 V	G	T	13 V	G	G.T.
2-1[illegible]	[illegible]	[illegible]	340		[illegible]	[illegible]	→	264[illegible]	[illegible]	→	26[illegible]	[illegible]	27.7
2-18			[illegible]	→	2.621	[illegible]		26[illegible]	2[illegible].14		2.65[illegible]	27.91	[illegible]8
2-2[illegible]					[illegible]	27.[illegible]		[illegible]	27.[illegible]	→	2.658	[illegible]	[illegible]
[illegible]					2.621	26.[illegible]		2.639	26.[illegible]		2.658	26.[illegible]	28.[illegible]
[illegible]				92	2621	25[illegible]	95	2638	26.[illegible]	95	2.656	[illegible]	28.0
2 [illegible]	Stopped charge												

23 MARCH 1953 TEST CYCLE #8 3 [illegible]

Time						I	T	V (11)	G	T	V (12)	G	T	V (13)	G	GT	[illegible]
1048	Commenced topping off					2.4	81	2.613		81	2.652		83	2.666			
1103								2.626			2.660			2.673			
1111								2.632			2.662			[illegible]			
1116								2.632			2.662			2.675			
1121								2.634			2.662			2.676			
1126								2.634			[illegible]			2.675			
1128	Stopped charge. Set up timing switch (1-12)																
1150.2	0					14.58											
	1.5			[illegible]		↓	87	[illegible]		88	[illegible]		90	[illegible]			
	6			[illegible]				1990			1983			[illegible]			
	12			6				1975			1965			1978			
	18							1958			1941			1960			
	24							1939			1921			1941			
	30							1918			1901			1920			
	36							1895			1883			1898			
	42			6				1862			1850			1863			
12[illegible]	48			3				18[illegible]			18[illegible]			182			
1240	Resumed charging at [illegible] rate																
1240	00					6.0											
	04						[illegible]	2.117		91	2.100		92	2.126			
	12							2.146			2.134			2.150			
	24							2.180			[illegible]			[illegible]			
	36							2.204			2.197			2.220			
	48							2.224			2.224			2.242			
									32.19			32.52			32.53	33.2°	

[illegible] → 48.25 48.25 43.21

23 March Test Cycle #8 3 [illegible]

Time						I	T	V	G	T	V	G	T	V	G	GT	f	Comments
1340	60	Continued [illegible] rate				6.0		2.2[illegible]5	[illegible]		2.248	32.52		2.266	[illegible]			
	1:12	[illegible]					92	2.273		94	2.274		94	2.295		33.9°		TVG =
	1:26	[illegible]					91	2.310		93	2.312		94	2.334				2.324
	1:28	Stopped charge [illegible]						2.316			2.319			2.338				
1410.2	0:00	Resumed charge				2.4	91			93			94				[illegible]	
	0:12					↓		2.2[illegible]			2.254			2.273			3.02	[illegible] 60
	0:24							2.266			2.265			2.2[illegible]				
	0:36							2.282			2.283			2.301				
	0:48						91	2.306		94	2.304		94	2.321			3.00	[illegible]
1510.2	1:00							2.33[illegible]			2.3[illegible]			2.350				
	1:12							2.401			2.377			2.4[illegible]			[illegible]	[illegible]
	1:25							2.515			2.504			2.526				
	1:36							2.564	[illegible]		2.576	31.15		2.593	[illegible]	[illegible]		
	1:42							2.575	[illegible]		2.588	30.[illegible]		2.60[illegible]	[illegible]	[illegible]	[illegible]	[illegible] 81
	1:48							2.580	29.91		[illegible]	30.31		2.61[illegible]	[illegible]	31.6		
	1:54							2.5[illegible]	[illegible]		[illegible]	29.[illegible]		2.62[illegible]	[illegible]	[illegible]		
	2:00							2.592	[illegible]		2.602	[illegible]		2.624	29.89	31.2		
	2:06							2.595	[illegible]		2.602	[illegible]		2.626	[illegible]	31.0	3.00	[illegible]
	2:12							2.598	[illegible]		2.60[illegible]	[illegible]		2.6[illegible]	[illegible]	[illegible]		
	2:18							[illegible]	[illegible]		[illegible]	[illegible]		2.6[illegible]	[illegible]	30.6		
	2:24							2.592	2664		2.599	[illegible]		2.6[illegible]	[illegible]	[illegible]		
	2:30							[illegible]	2.6[illegible]		2.599	2661		2.616	[illegible]	[illegible]		
	2:31	Stopped charge																

25 MARCH 1953 TEST CYCLE # 4 100 N/m

				I	T	V	G	T	V	G	T	V	G	GT	f
[illegible]	0	Commenced [illegible]		2.40											[illegible]
	0-09				[illegible]	2663		[illegible]	26[illegible]		80	2705			
	0-15					2.666			[illegible]			2.70[illegible]			
	23	Loose voltmeter connect [illegible]				2660			2622			2703			
	28					662			[illegible]			2.702			
		Adjusted [illegible] charging [illegible]													
[illegible]	0	Commenced discharge		4.97	81			84			85				
	0-015		3.15	↓		1986			1992			2.006			
	06		3.5			1,997			1990			2.001			
	[illegible]		6			1979			1972			1,983			
	18					19[illegible]0			[illegible]			1,963			
	24					1939			1934			1,942			
	[illegible]					1,920			[illegible]			[illegible]			
	[illegible]					[illegible]			[illegible]			,854			
	42					[illegible]			[illegible]			[illegible]			
[illegible]	0-47	Stopped discharge				1,503			1,798			1,804			
[illegible]	0-00	Started charge		6-	8[illegible]			86			87				
	0-06					[illegible]			[illegible]			[illegible]			
[illegible]	[illegible]	Changed to higher [illegible]			Note [illegible]				←						
[illegible]	[illegible]	[illegible]													
	0-18					2,188			2.186			2.2[illegible]			
	0-24					2.202			2.203			2.220			
	0-36					2222			2235			2.241			
	0-48					2,241			2.252			2266			

CYCLE # 9	25 MARCH '53	100% I	I	T	V	G	T	V	G	T	V	G	GT	f	RPM
		[illegible]				49.14			49.62			[illegible]			
12[illegible]	1-00	Commenced, start rate	6 00		2269			[illegible]			2,291				
	1-12			8[illegible]	2 300		[illegible]	2 309		[illegible]	2 322				T[illegible] 2.3[illegible]
	1 [illegible]	Stopped charge		85	2 397		88	2.341		[illegible]	2.366				
1229		Resumed @ finishing rate	2 40											100	
	0-06		↓	86	2.2[illegible]	[illegible]	88	2.263	31.80	[illegible]	2276	31.95		99.9	1998.5
	0-12				2268			2270			2,282				
	0-24				228[illegible]			2.[illegible]			2.300				
	[illegible]				2.[illegible]			2.299			2 312				
	[illegible]				2.31[illegible]			2.318			2.332			100[illegible]	2012
	1 [illegible]				[illegible]			2.341			2.356				
	1-[illegible]			85	2.379		88	2.379		89	2.398				
	1-24				2.445			2,440			2,452			100	2000
	1-36				2.543			2.562			2.568				
	1-49				2.58[illegible]	30.6		2.610	30.14		2.611	[illegible]	29.		
	1-5[illegible]				2.593	30.4		2619	[illegible]		2.627	[illegible]	29.0		
	[illegible]			87	2.600	29.81	91	2.625	29.26	92	2.631	29.45	29.0		
	2-00				2.604	2924		2.631	2865		2.640	29.08	29.0		
	2-12				2.606	28.[illegible]		2.6[illegible]	28.22		[illegible]	[illegible]	29.0		
	2-1[illegible]				2.608	28.[illegible]		2.634	[illegible]		2.644	28.18	29.0		
	2-[illegible]				2.610	27.15		2.636	27.09		[illegible]45	[illegible]	29.0		
	2-[illegible]			→	2.612	27.[illegible]	→	2.637	26.36	→	2.646	27.18	29.0	[illegible].9	[illegible]
	[illegible]				2.607	26.64		2.636	26.[illegible]		2.64[illegible]	[illegible]	29.0		
	[illegible]				2.606	26.13		2.634	25.94		2.644	26.[illegible]	29.0		
	[illegible]				2.606	25.[illegible]		2.633	24.[illegible]		2.644	[illegible]	29.1		
	2 [illegible]	Stopped charge													

26 March 1953 Test run # 10 400 ~

				I	T	V (11)	G	T	V (12)	G	T	V (13)	G
approx ↓													
1032	00	Top off		2.4		~~2639~~			~~2678~~			~~2686~~	
	04			↓		2639			2678			2686	
	06					2642			2679			2690	
	12					2643			2680			2692	
	18					2645			2680			2694	
→	21					2643			2679			2693	
	23					2642			2678			2692	
	24	Secured											
1156	0	Comm. discharge											
	0-02			14.99	83	2006		85	202		87	2014	
	06					2003			1998			2007	
	12					1.986			1.978			1.988	
	18					1.965			1.959			1.966	
	24					1.946			1.939			1.948	
	30					1.922			1.918			1.923	
	36					1.898			1.890			1.898	
	42					1.86[illegible]			1.854			1.859	
1144	48	Stop disch				1.812			1.[illegible]04			[illegible]810	
1145	0	Start charge 6.0											
	0-3			↓	86	2.102		88	2.100		89	2.111	
	0-12					2.148			2.146			2.162	
	24					2.195			2.187			2.200	

26 March, 1953 Test run # 10 400 ~

time	—				I	T	V (11)	G	T	V (12)	G	T	V (13)	G	GT	(1.1)	+ 3+28.573	
	0:36				6.00		2.211	(48.17)		2.214	(48.19)		2.225	(48.17)				
	0:48				↓		2.235			2.239			2.252					
1245	1:00						2.258			2.263			2.280					
	1:12					86	2.[illegible]76		88	2.29[illegible]		89	2.308					TVC = 2.352
	1.24						2.322	32.73		2.328	32.505		2.345	32.48				
	1:26	Stopped 1st TVC										89	2.352					
1312	0-00	Resumed			2.40			32.73			32.505			32.48				
	0-02	$\boxed{\text{hrs}}$					2.248			2.259			2.272					
	0-12	0.2					2265			2268			2283					
	0-24	0.4			2.40		2280			2282			2299					
	0-36	0.6					2.298			2.302			2.317			3500		
	0-48	0.8					2.311			2.321			2.338					
	1-00	1.0				85.5	2.349		88	2.351		88.[illegible]	2.363					
	1-12	1.2					2.389			2.399			2.412			3500		
	1-24	1.4					2.482			2.497			2.518					
	1-36	1.6					2.570			2.592			2.611					
→	1-42	1.7					2.583	3.135		2.604	3105		2.626	3100	28.7			
	1-48	1.8				87	2.593	30[illegible]	90	2.621	[illegible]060	90.5	2.6[illegible]7	3.255	28.7	3500		
	1-54	1.9					2.603	3041		2.628	3012		2.643	3.12	28.6			
	2-00	2.0					2.605	2995		2.632	2960		2.64[illegible]	2.[illegible]59	28.3			
	2-06	2.1					2.608	2940		2.636	2907		2.652	2911	28.4			
	2-12	2.2					2.605	2888		2.636	2851		2.654	2.855	28.[illegible]	3500		
	2-18	2.3				→	2.610	2838	→	2.637	2796		[illegible].654	2803	28.8			
	2-24	2.4					2.610	2.784		2.636	2.746	→	2.65[illegible]	2752	28.9			
	2-30	2.5					2.610	2.734		2.636	2.[illegible]		2.65[illegible]	2.[illegible]16	29.0	3500		
	2-36	2.6					2.605	2.693		2.636	2.632		2.651	2.646	28.9			

2-37 Stop charge

1 April 1953 Cycle # 11 7¾ ~

			I	T (11)	V (11)	G (11)	T (12)	V (12)	G (12)	T (13)	V (13)	G (13)
0805			0		2121			2124			2137	
0809	00	[illegible] off	2.4									
	06				2643			2681			2694	
	08			72			73			75		
	12				2660			2690			2702	
	18				2668			2696			2706	
	24				2664			2696			2703	
	24:07	[illegible]		75			76.5			78.5		
		Commence discharge										
0837	00		14.99									
	01		↓		1980			1979			1991	
	02:30				1984			1983			1995	
	06				1981			1978			1986	
	12				1963			1959			1969	
	18			77	1945		79	1940		81	1951	
	24				1926			1921			1928	
	30				1905			1900			1908	
	36				1879			1875			1880	
	42				1840			1833			1839	
	48			80	1768		83	1759		85	1762	
0927	0	Commenced charge	6.00									
	05			5	2.124			2.122			2.135	
	12			7	2.152			2.152			2.164	
	24			12	2.188			2.188			2.202	

1 April 1953 Cycle # 11 7¾ ~/sec

			I	T (11)	V (11)	G (11)	T (12)	V (12)	G (12)	T (13)	V (13)	G (13)	GT	f
1003	0-36	Continuing start [illegible]	6.0		2215	(48.22)	~~2.~~	2.219	(48.24)		2230	(48.28)		
	0-48				22[illegible]			2.241			2.256			
1027	~~1-00~~		↓	83	2262		85	2.267		87	2.275			
	1-12			83	2.290	32.52	85	2.300	32.52	86	2312	32.38		
	1-24			82	2.328		84.5	2.338		85.5	2.349			
	1-28	Stop 1.467 hrs.			2.346			2.352			2.364			
1102	0-00	[illegible]	2.4		~~2244~~			~~2.248~~						7.76
	0-02		↓	82	2.241		85	2.248		86	2259			
	0-12				2268			2.273			2.283			
	0-24				2.281			2.290			2.301			
	0-36				2.303			2.307			2.311			7.79
	0-48				2.324			2.329			2.338			
	1-00			83	2.358		86	2.358		87	2.363			
	1-12				2415			2411			2415			
	1-24				2519			2536			2524			
	1-36				2580			26[illegible]8			2614			
	42				2.582	30.88		2.621	30.74		2.627	30.83		
	1-48				2.593	30.45		2628	30.16		2638	[illegible]		
	1-54				2603	29.86		2.634	29.85		2.643	29.96	27.8	
	2-00				2.628	29.46		2639	29.23		2643	29.15	27.9	7.75
2.1	2-06	Bad connection [illegible] voltage		→	2.611	29.11	→	2.640	28.62		2.637	28.94	27.9	
	2-12				2.610	28.49		2640	28.13		2645	28.48	28.0	
	2-18				2607	27.98		2.640	27.51		2.649	27.95	28.0	
2.4	2-24				2608	27.47		2639	27.04	→	2.650	27.47	28.0	
	2-30				2.607	26.15		2.639	26.45		2.649	26.93	28.0	
	2-36				2.604	2646		2.639	25.91		2.648	26.46	28.0	7.80
	2-37.2 stopped													

(Temp. [illegible] on [illegible] or [illegible])

Voltage ripple 4054 peak to peak [illegible]

8 APRIL 1953 TEST CYCLE #12 STEADY

					I	T	11 V	G	T	12 V	G	T	13 V	G	GT		
0840	Commenced [illegible]				2.4												
0	0-04				↓	59	2.720		58.5	2.750		61	2.759				
	09						2.721			2.752			2.762				
	14						2.721			2.755			2.762				
	19						2.720			2.755			2.762				
	24					62.5	2.719		63.5	2.751		67	2.761				
0909	0	Comm. disch			4.99												
	01.5						1.968			1.959			1.977				
	06				↓		1.962			1.948			1.966				
	12						1.946			1.932			1.988				
	18						1.928			1.916			1.952				
	24						1.908			1897			1912				
	30						1.884			1.871			1.885				
	36						1.852			1.840			1.853				
	42						1.800			1.782			1.796				
0957	47.5						1.6[illegible]			1.620			1.615		Note: L.V.L. = 1.65		
	48	Secured				71			72	1.60		74.5					
										— Low cell —							
0959	0	Comm. charge			6.00												
	02						2.110			2.113			2.118				
	15						2.169			2.171			2.181				
	24				↓		2.199			2.201			2.212				
	36						2.223			2.230			2.241				
	48					76	2.250		79	2.259		79	2.281				

8 APRIL 1953 TEST CYCLE #12 CTD STEADY

					I	T	11 V	G	T	12 V	G	T	13 V	G	GT		
1059	1-00	Continue SR			6.00		2.276	(48.23)		2.284	(48.25)		2.299	(48.28)		[illegible]	
	1-12					78	[illegible]	33.46	80	2.319	32.95	81	2.332	33.45		TUG [illegible] 2.573	
	1-24				↓	79	2.344		81	2.358		82	2.367				
	1-26	Secured SR															
1126	0	Start FR			2.40												
	0-03						2.264			2.268			2.281				
	0-13				↓		2.277			2.280			2.293				
	0-24						2.287			2.296			2.306				
	0-36						2.305			2.312			2.323				
	0-48						2.325			2.330			2.342				
	1-00					81	2.352		83	2.360		83.5	2.369				
	1-12						2.401			2.410			2.416				
	1-24						2.498			2.527			2.525				
	1-36						2.579	3141		2.610	3133		2.616	3142	25.7		
	1-42						2.591	3105		2.614	3089		2.622	3104	25.6		
	1-48						2.600	3065		2.634	3038		2.641	3059	25.6		
	1-54					84	2.606	3023	87	2.640	2992	87	2.647	3016	25.6		
	2-00						2.610	2973		2.644	2933		2.652	2965	25.5		
	2-06						2.612	2927	→	2.643	2886		2.653	2919	25.6		
	2-12						2.614	28.75		2.643	28.31	→	2.656	28.70	25.8		
	2-18					→	2.615	28.29		2.643	27.75		2.656	28.19	25.9		
	2-24					87	2.612	27.77	91	2.642	27.15	91	2.656	27.69	26.0		
	2-30						2.609	27.32		2.642	26.64		2.655	27.19	26.0		
	2-31-05	Secured.															

28 April Cycle 81 [illegible]

[illegible]	Comm[illegible]		[illegible]										
	[illegible]			75	[illegible]		7[illegible]	[illegible]		[illegible]	[illegible]		
	[illegible]			77	[illegible]		71	[illegible]		81	[illegible]		
	[illegible]	St[illegible]											
		Comm[illegible]	[illegible]	77			8[illegible]			81.5			
	01				1.[illegible]			1.967?			1.98?		
	05				1.982			[illegible]			1.986		
	10	Stopped [illegible]		78	1.968		70.5?	1.95?		82	1.972		
		Calib[illegible]				(48.18)			(48.20)			(48.34)	
10-25?	-05	Comm[illegible]	2.4			32.00			32.30			32.46	
11.5	10?	[illegible]											
	0[illegible]			78	2.144?		81	2.192?		82.5	2.202		
	[illegible]				2.210			2.201			2.220		
	1-18?				2.234			2.254			2.242		
	31	Comm[illegible]			2.277			2.278			2.292		
	48			77	2.322		82	2.330		[illegible]	2.342		
1212.5	[illegible]			[illegible]	[illegible]		82	2.495		[illegible]	[illegible]		
[illegible]	1-06				2.[illegible]	[illegible]		2.641	31.74?		[illegible]	[illegible]	
[illegible]	1-12				2.628	31.[illegible]		2.662	31.23		2.679	31.48	27.6
[illegible]	1-18				2.6[illegible]	30.63		2.669	30.76		2.693	31.02	27.2
[illegible]	[illegible]				2.642	30.10		2.692	30.21		2.687	30.52	27.0
[illegible]	1-30				2.640	29.50		2.673	29.55		2.685	29.71	27.0
[illegible]	1-36				2.6[illegible]	29.[illegible]		2.670	29.0		2.683	29.53	27.0
	1-42				2.641	28.51		2.668	28.55		2.682	29.01	26.8
115-		Stopped											

28 April Cycle 82 [illegible] current

			I			G	T						T
12 48	Comm	[illegible]	14.99?	81.5			85			85			
	[illegible]				2.010			2.000			2.019		
	0-05				1.9[illegible]			[illegible]			2.002		
12 58	[illegible]	Stopped [illegible]		81.5	1.972		85	1.952		85	1.979		
12[illegible]	[illegible]	[illegible] F.R	2.4			32.31			32.37			32.67	
	02				2.160			2.157			2.168		
	12				2.205			2.206			2.217		
	24				2.227			2.224			2.238		
	36				2.2[illegible]			2.252			2.264		
	48				2.306			2.309			2.323		
[illegible]	1-00			82.5	2.481		85	2.5[illegible]		85	2.639		
	1-06				2.608	31.81		2.643	31.71		2.665	32.10	28.0?
	1-12				2.624	31.51		2.659	31.45		2.678	31.84	28.0
	1-18				2.632	31.00		2.6[illegible]	30.87		2.682	31.34	27.9
	1-24				2.637	30.45		2.666	30.25		2.684	30.80	27.8
	1-30				2.639	29.97		2.665	29.77		2.684	30.31	27.7
	1-36				2.638	29.41		2.669	29.15		2.682	29.79	27.7
	1-42			86	2.631	28.78	90	2.651	28.65	90	2.680	29.25	27.8
	1-43	Stopped											

29 April 1953 Cycle 83 STEADY

			I	T	V_{11}	G	T	V_{12}	G	T	V_{13}	G	GT
0828	0-00	Commenced tapping off	24		2.668								
	05			72.5	~~2668~~		74	2697		76	2.720		
	12				2.678			2.702			2.721		
	18				2.679			2.702			2.721		
	21				2.679			2.702			2.721		
0830	0-00	Comm. discharge	14.99		~~1.98~~								
	01			75	1.[illegible]		78	1.969		79.5	1.987		
	05				1982			1974			1987		
	10			76	1764		79	1.154		80	[illegible]		
0841	00	Start charge	2.4		~~32.26~~	32.26		~~32.24~~	32.29			32.??	
	06		↓		2.197			2.196			2.207		
	12				2.211			2.209			2.220		
	24				2.232			2.233			2.242		
	36				2.261			2.260			2.275		
	48			77	2.321		80	2.325		81	2.340		
0941	1-00				2.473			2.526			2.533		
	1-06				2.619	31.87		2.655	32.35	26	2.662	32.61	26.4
	1-12				2.644	31.42		2.681	31.91		2.692	32.22	26.0
	1-18				2.656	30.87	→	2.695	31.27		2.700	31.62	26.1
	1-24			→	2.659	30.6	→	2.685	30.71	→	2.701	31.1	26.0
	1-30				2.659	29.90		2.685	30.13		2.699	30.64	26.0
	1-36				2.657	29.70		2.682	29.31		2.6[illegible]	30.09	26.2
	1-36½	Stopped		82			85			86			

Cycle 84 29 April 1953 STEADY

			I	T	V_{11}	G	T	V_{12}	G	T	V_{13}	G	G?	
10[illegible]	0	Start of discharge	14.[illegible]			[49.18]			[48.20]			[49.[illegible]]	[illegible]	[illegible]
	01			82	2.[illegible]		85	2.[illegible]		[illegible]	2.[illegible]			
	05				2.[illegible]			1.99[illegible]			2.[illegible]			
10[illegible]	10			83½	1.9[illegible]		86	1.90[illegible]		[illegible]	1.[illegible]			
[illegible]	0	Start charge	24			29.06			29.[illegible]			29.[illegible]		
	01				2.[illegible]			2.49			2.[illegible]			
	12				2.20[illegible]			2.201			2.[illegible]			
	24				2.2[illegible]			2.223			2.[illegible]			
	36				[illegible]			2.2[illegible]			2.[illegible]			
	48			81	2.3[illegible]		84	2.31[illegible]		[illegible]	2.3[illegible]			
80	1-00				2.[illegible]			2.[illegible]			[illegible]			
	1-06				2.6[illegible]	29.6		[illegible]	[illegible]		[illegible]	[illegible]	27.[illegible]	
	1-12				2.6[illegible]	28.[illegible]		2.[illegible]	[illegible]		[illegible]	[illegible]	27.0	
	1-18				2.641	27.[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	27.0	
	1-24			→	2.6[illegible]	[illegible]	→	[illegible]	[illegible]	→	[illegible]	[illegible]	27.0	
	1-30				2.64	26.[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	27.1	
	1-36				2.6[illegible]	25.9[illegible]		[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	
	[illegible]	Stopped		85			[illegible]			[illegible]				

30 APRIL 1953 cycle 85 STEADY

			I	T	V (11)	G	T	V (17)	G	T	V (18)	G	GT	
1241		Commenced charge	2.4			[48.18]			[48.18]			[48.19]		[Bottle type]
	04			71	2.670		73	2.702		74.5	2.722			
	12				2.678			2.708			2.724			
	18				2.681			2.710			2.724			
	24				2.681			2.708			2.722			
1306	25	Secured												
1307	00	Commenced discharge	N49		~~1980~~			~~1972~~			~~1991~~			
	01			73.5	1980		77	1972		78	1991			
	05				1.982			1.974			1.989			
	10			75	1.963		77.5	1.954		78.5	1.965			
1318	00	Comm charge	2.4											
	02		*		2.164	32.68		2.168	32.66		2.178	32.82		
	12				2.216			2.215			2.223			
	24				2.238			2.236			2.243			
	36				2.264			2.262			2.280			
	48			76	2.334		79	2.3[illegible]		80	2.3[illegible]			
	1-01				2.445			2.494			2.4[illegible]			
	1-06				2.619	32.21		2.658	32.17		2.665	32.34	27.2	
	1-12				2.651	31.85		2.682	31.71		2.696	31.96	27.0	
	1-18			→	2.659	31.36		2.687	31.16	→	2.702	31.45	26.8	
	1-24				2.659	30.81	→	2.690	30.57		2.701	30.71	26.9	
	1-30				2.659	30.21		2.686	29.95		2.701	30.37	27.0	
	1-36	Stopped		83	2.653	29.66	86	2.682	29.35	87	2.700	29.84	27.0	
						110			122			161		

METER DATA 3/4/53

TYPE	RANGE	MODEL	SERIAL	APPLICATION	CALIBRATED
AMMETER	0-25 A DC	[illegible] 45	21455	DISCH CURRENT	YES
"	0-3 DC	do.	57592	COMPARISON CHG. CURRENT	AT 2.4 [illegible]
"	0-5 DC	do	24582	CHG. CURRENT	YES
"	0-10 DC	do	27771	do.	YES
"	0-3 DC	do	[illegible]	AMPERITE CELL CURRENT	AT 2.4 [illegible]
"	0-15 DC	do	31116	do	YES
VOLTMETER	0-3 DC	do	24335	CELL VOLTAGE	YES
"	0-3 DC	do	24336	SAME	YES
[illegible]	20-80 AC	[illegible]	10-124		
		J.G BIDDLE	161-USN-202115	A.C. [illegible]	NO
BRUSH RECORDERS		BL 202	602		[illegible]
[illegible] E		[illegible] 309 H	7683		
[illegible]	0-[illegible] °F	[illegible]	NONE	CELL [illegible] ELECT.	[illegible]
"	20-150 °F	ALA Mfg Co.	393	" [illegible] "	[illegible]
"	20-150 °F	EXIDE [illegible]	NONE	" [illegible]	[illegible]
	10-[illegible] C	UNKNOWN		" [illegible]	[illegible]
GALVANOMETER	-	L&N			
VARIABLE RATIO [illegible]					